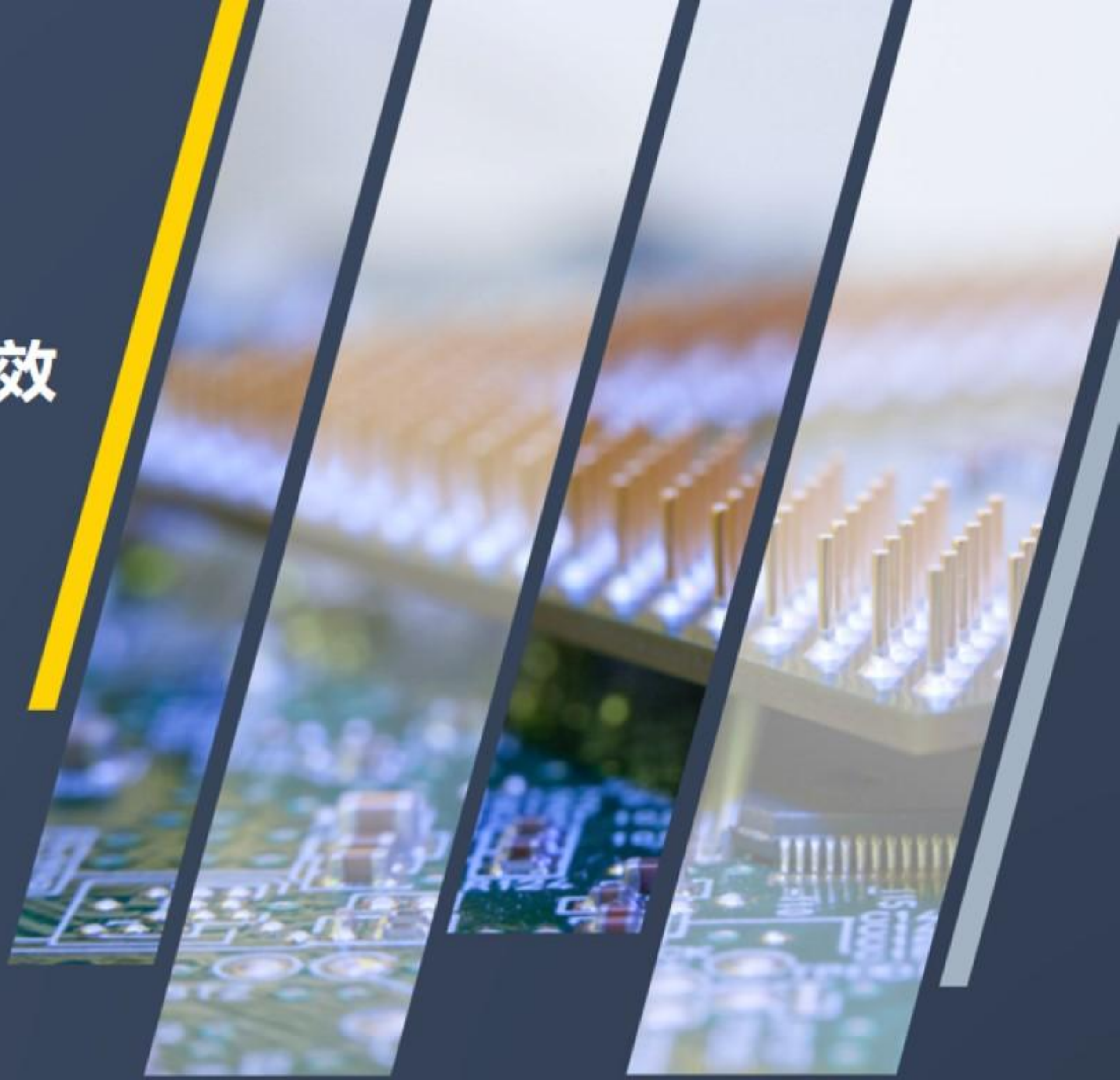
毫米波封装天线设计及全波分析有效方法



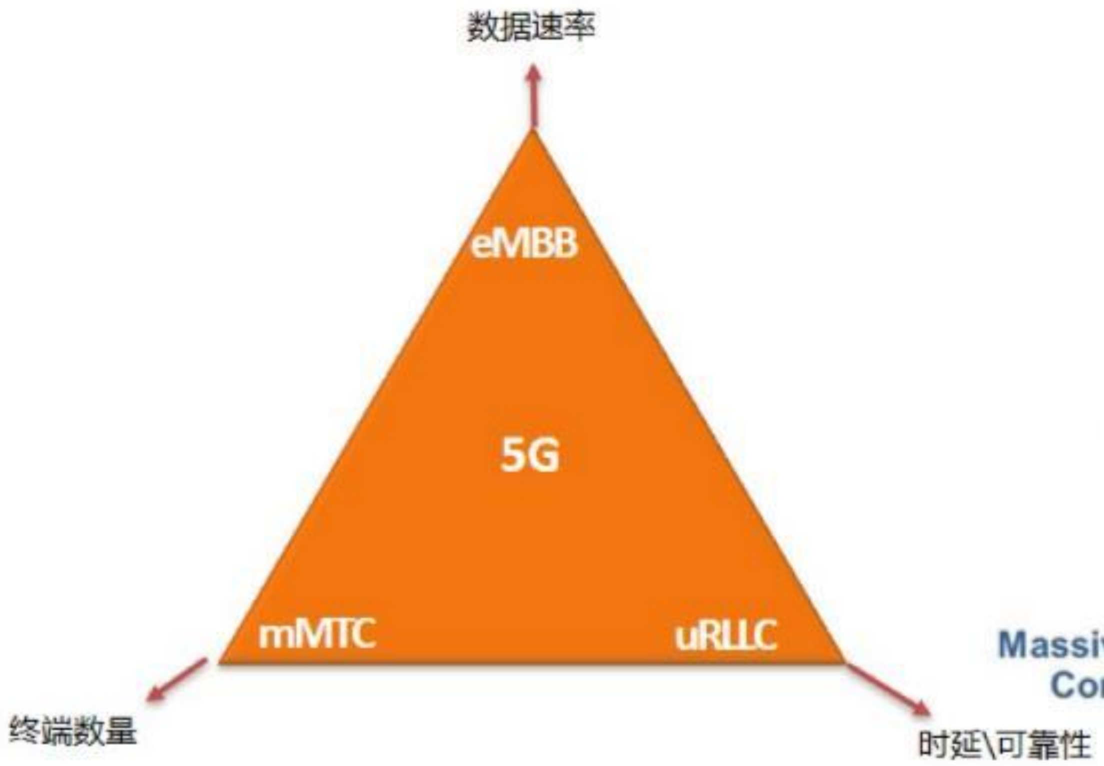
Author : Cong Li ANSYS

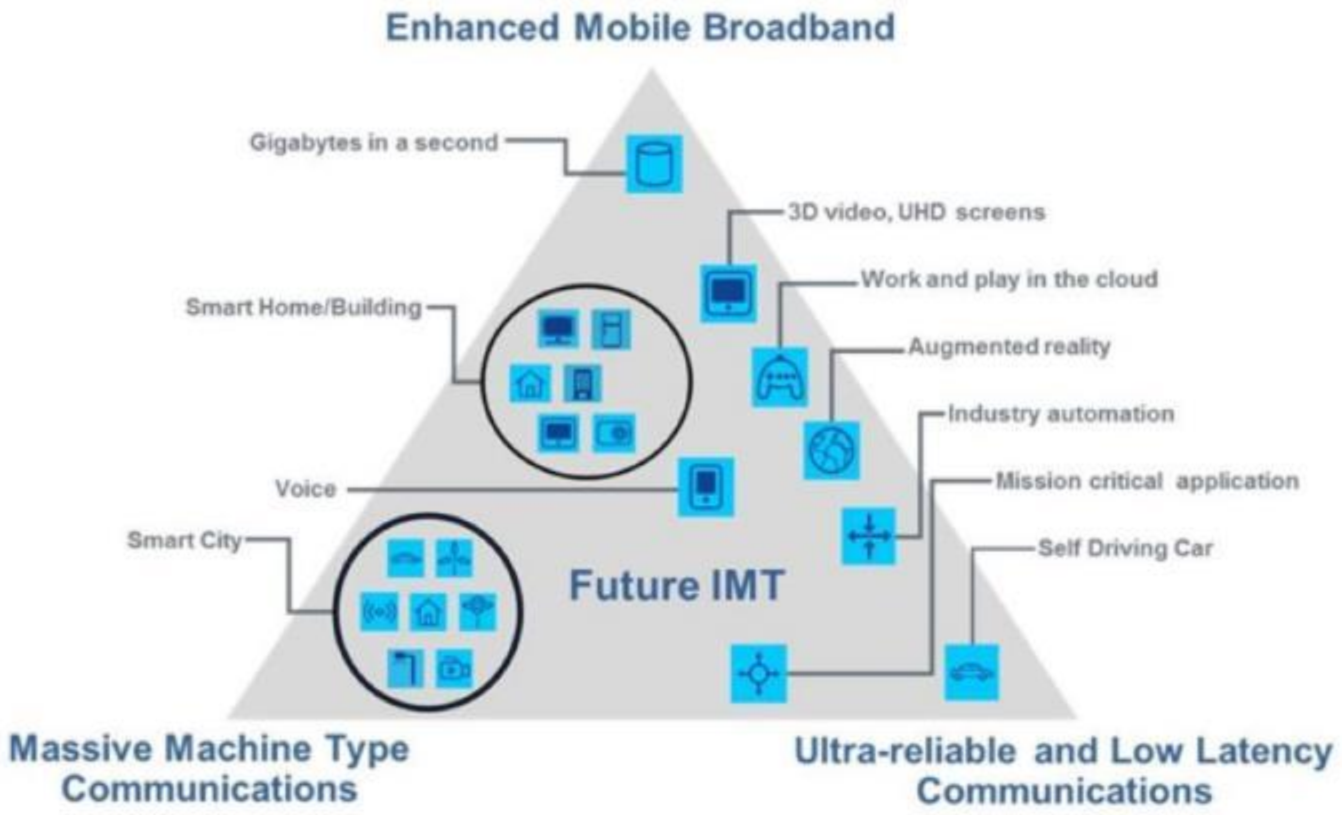
Presenter: Xu Zhang ANSYS

什么是5G?

- 5G是将现有（2G，3G，4G LTE，Wi-Fi等）以及新型技术（毫米波）所有无线技术的融合，5G将改变我们所感知的室内和室外无线网络的连接方式。

5G概念





xMBB： extreme Mobile Broadband 增强移动宽带

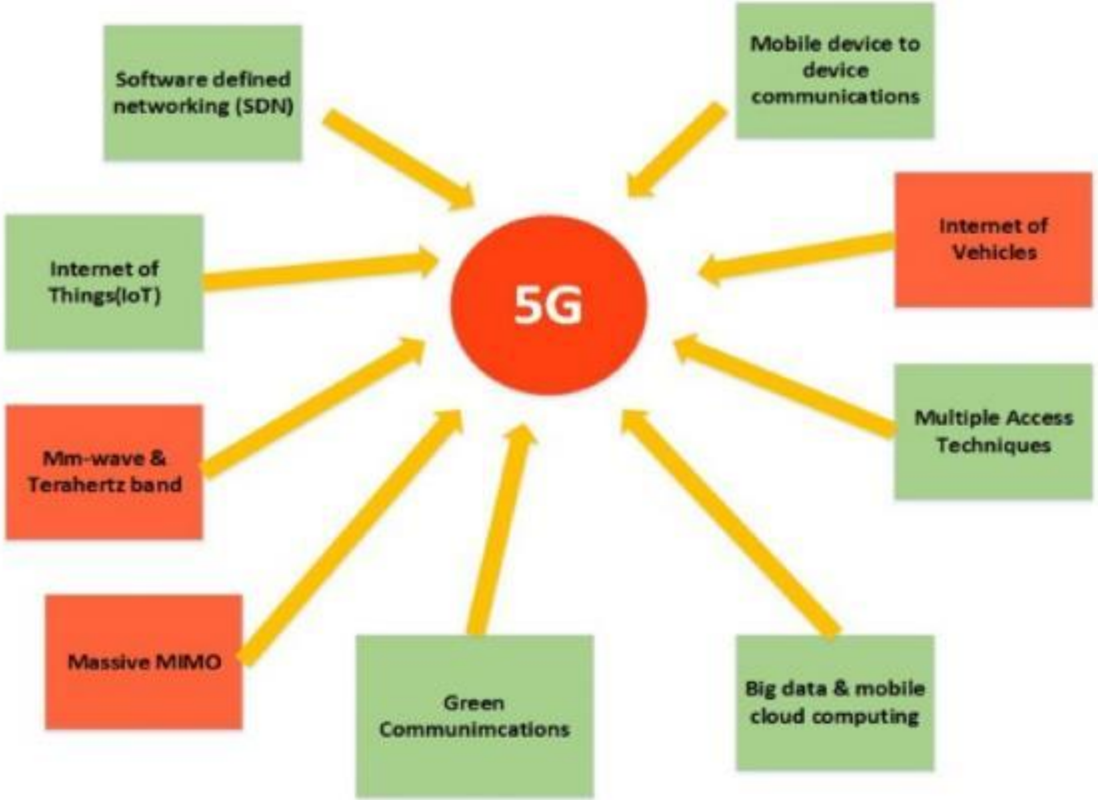
mMTC： massive Machine Type Communication 大规模机器类通信

uRLLC： Ultra-reliable and low latency communication超可靠低时通信

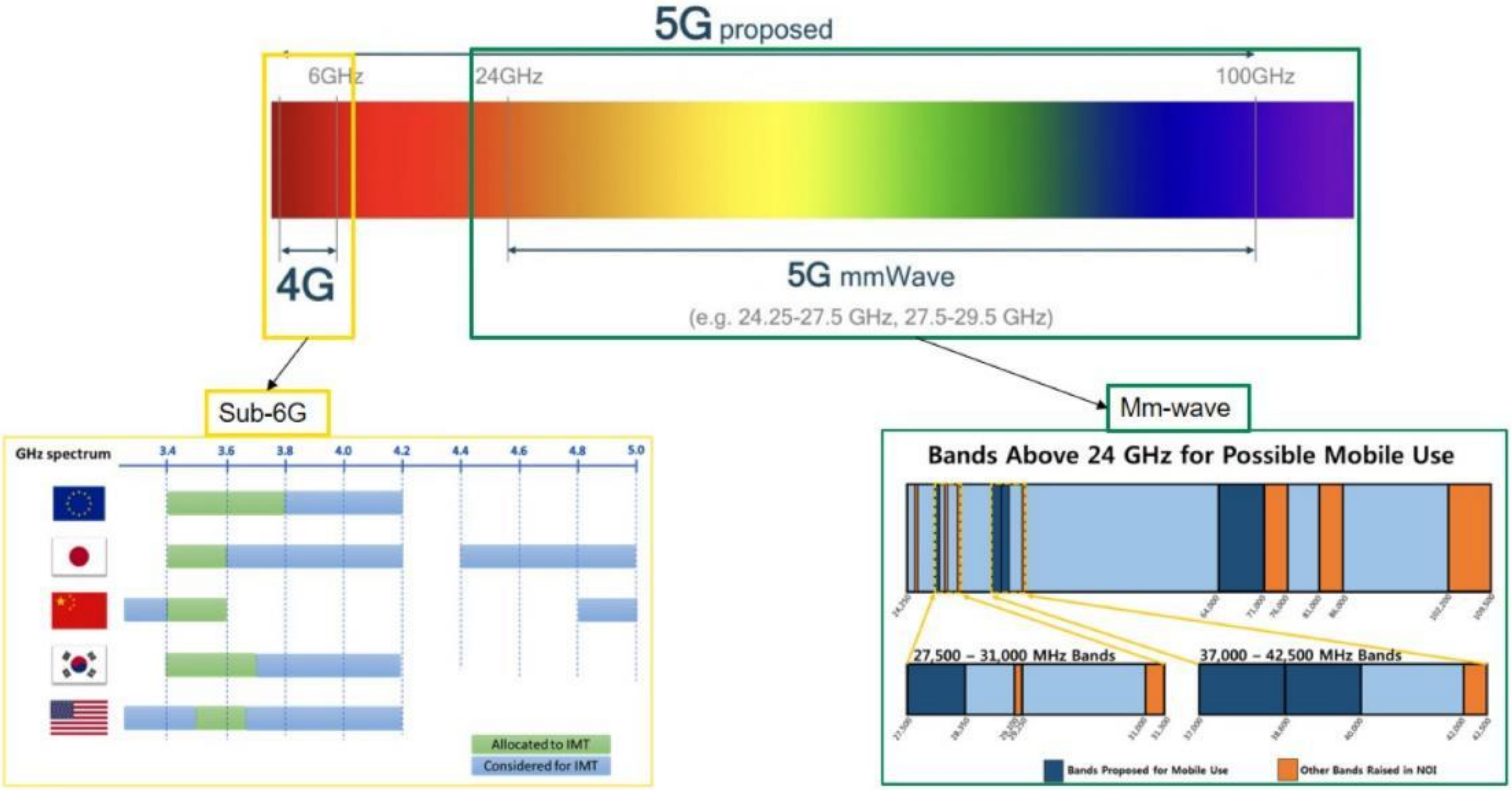
5G关键技术

5G 候选技术

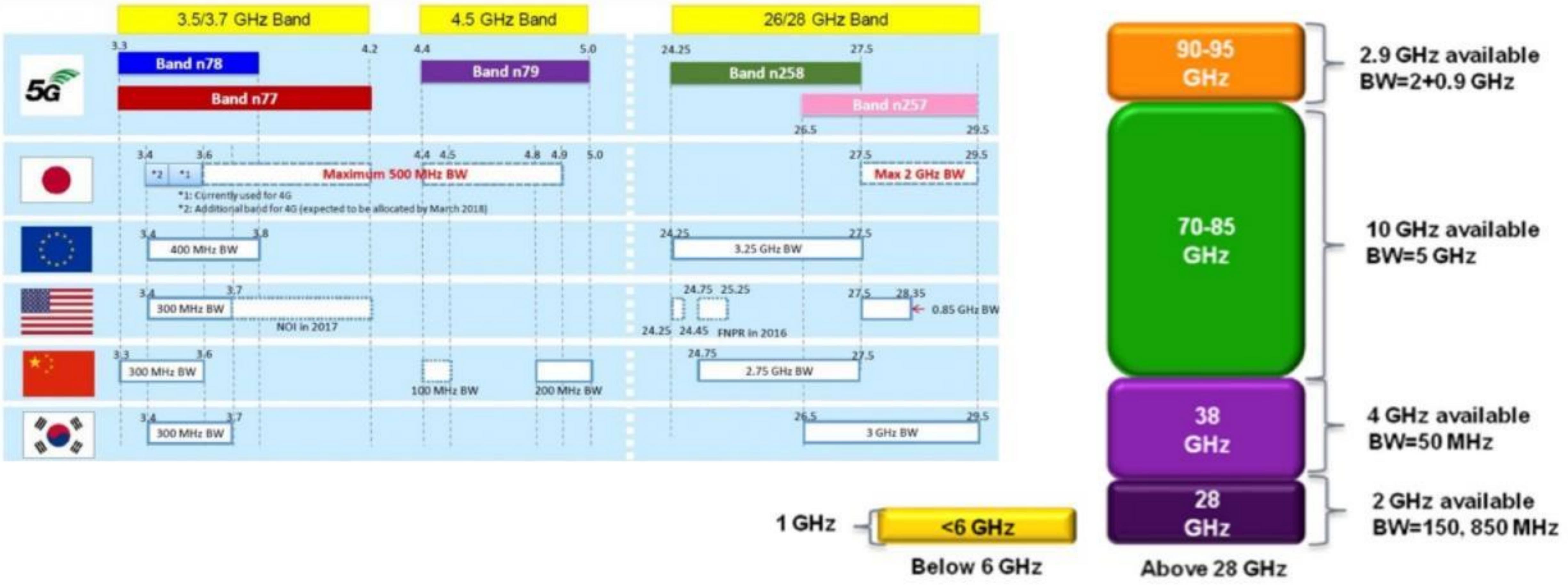
- 超密集无线网络
- 大规模天线
- 毫米波通信
- 频谱灵活使用
- 波形及多址
- 终端直通



5G频段


5G proposed
6GHz
24GHz
100GHz
4G
5G mmWave
(e.g. 24.25-27.5 GHz, 27.5-29.5 GHz)
Sub-6G
Mm-wave
GHz spectrum
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
Allocated to IMT
Considered for IMT
Bands Above 24 GHz for Possible Mobile Use
27,500 – 31,000 MHz Bands
37,000 – 42,500 MHz Bands
Bands Proposed for Mobile Use
Other Bands Raised in NOI

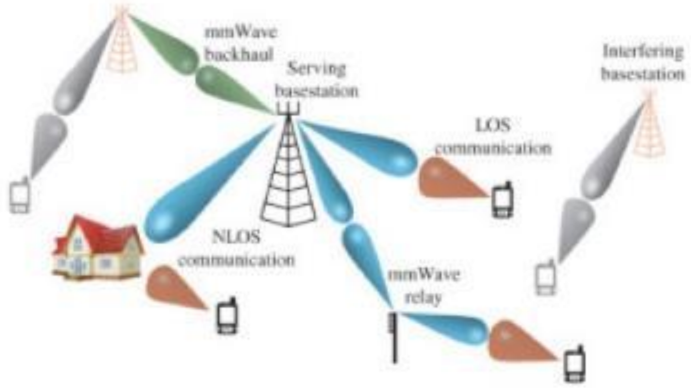
5G全球频谱分布



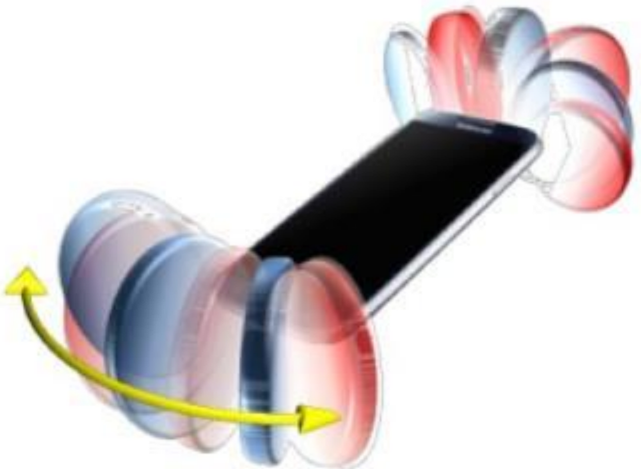
3.5/3.7 GHz Band
4.5 GHz Band
26/28 GHz Band
Band n78
Band n77
Band n79
Band n258
Band n257
Maximum 500 MHz BW
Max 2 GHz BW
*1: Currently used for 4G
*2: Additional band for 4G (expected to be allocated by March 2018)
400 MHz BW
3.25 GHz BW
300 MHz BW
NOI in 2017
FNPR in 2016
0.85 GHz BW
300 MHz BW
100 MHz BW
200 MHz BW
2.75 GHz BW
300 MHz BW
3 GHz BW
90-95 GHz
2.9 GHz available
BW=2+0.9 GHz
70-85 GHz
10 GHz available
BW=5 GHz
38 GHz
4 GHz available
BW=50 MHz
28 GHz
2 GHz available
BW=150, 850 MHz
1 GHz
<6 GHz
Below 6 GHz
Above 28 GHz

基站通信与终端通信

Point to point communication



Cellular mobile communication



- Antenna with narrow beam and high gain > 30dBi
- But small coverage

- High antenna gain means high link gain, and high capacity(high data rate, high quality etc.)
- if we want to have high antenna gain as well as wide coverage, what should we do? How to overcome the contradiction between the link gain and coverage?

- Antenna with wide beam and low gain ~ 14dBi
- But wide coverage

毫米波的挑战

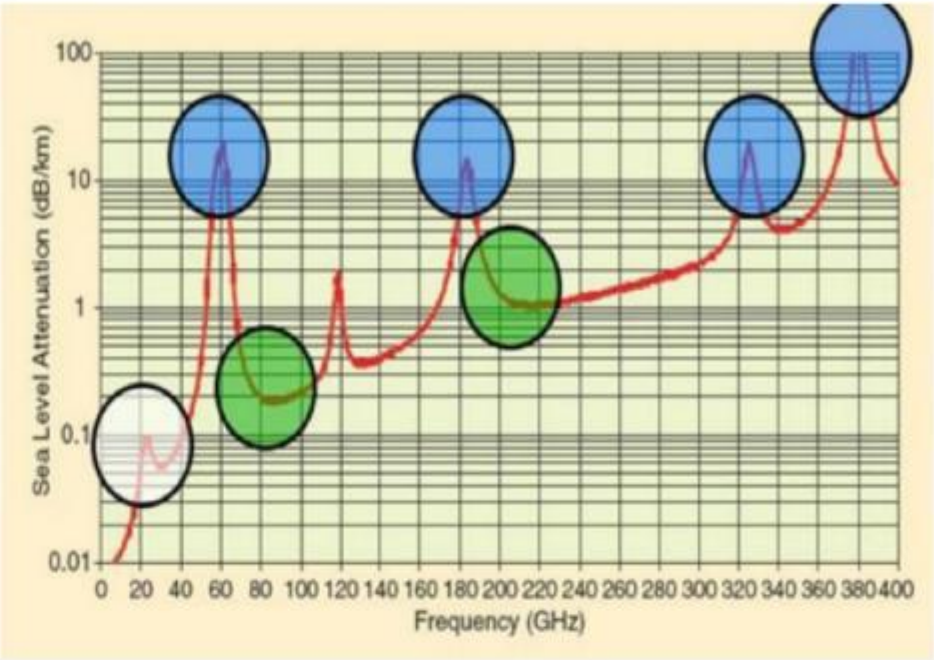
$$Friis\ Free\ Space\ Equation: P_{RX} = \frac{P_{TX} G_{TX} G_{RX} \lambda^2}{(4\pi R)^2}\ where$$

P_{TX} *is transmit power* P_{RX} *is receive power*

G_{TX} *is transmit antenna gain* G_{RX} *is receive antenna gain*

λ *is wavelength*

R *is distance between transmitter and receiver*



For WLAN system,fc = 2.4GHz, BW=20MHz, Linked budget loss :
20*log10(1/2.4)+10*log10(1/2e6) =-80dB
For mm-wave antenna system like 60GHz, fc = 60GHz,BW=2GHz,Linked budget loss :
20*log10(1/60)+10*log10(1/2e9)=-128dB
i.e. In order for mm-wave system to achieve similar link budget as WLAN system with similar P_{TX}, we need to rely on directional antenna **point to point** communication with high gain G_{TX} and G_{RX}.

  ANSYS

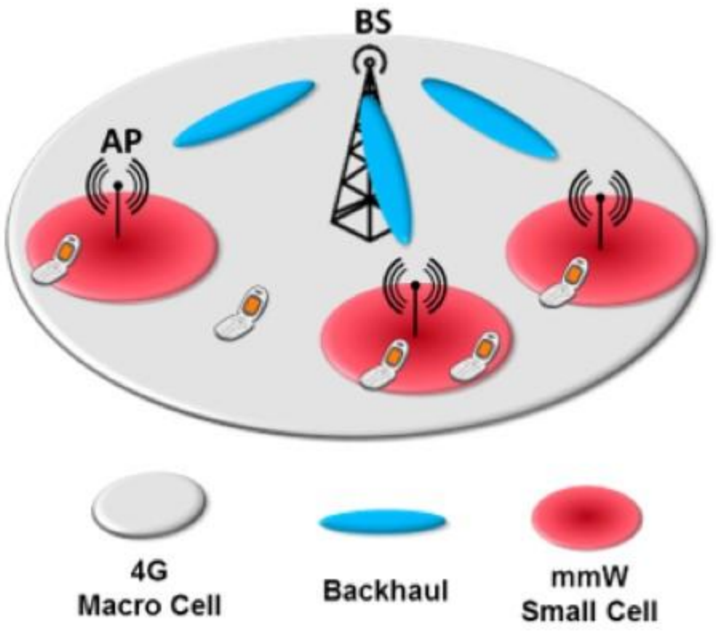
5G Overview Applications

Automotive

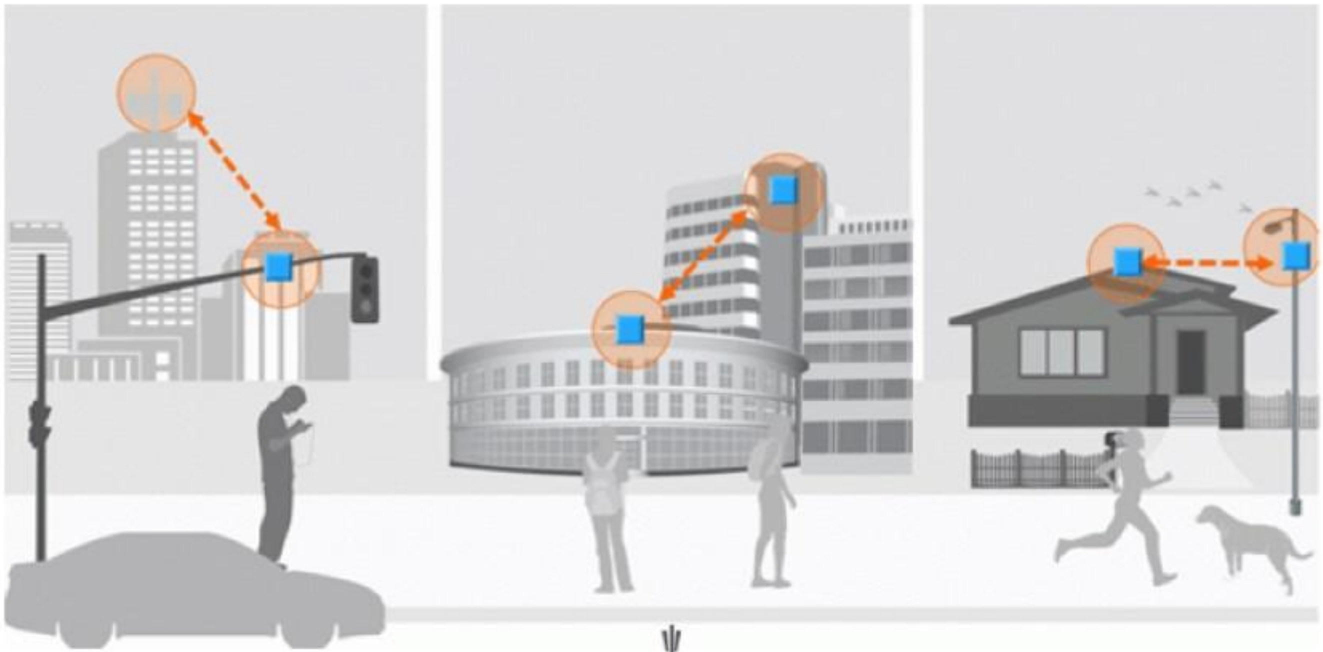
Infrastructure

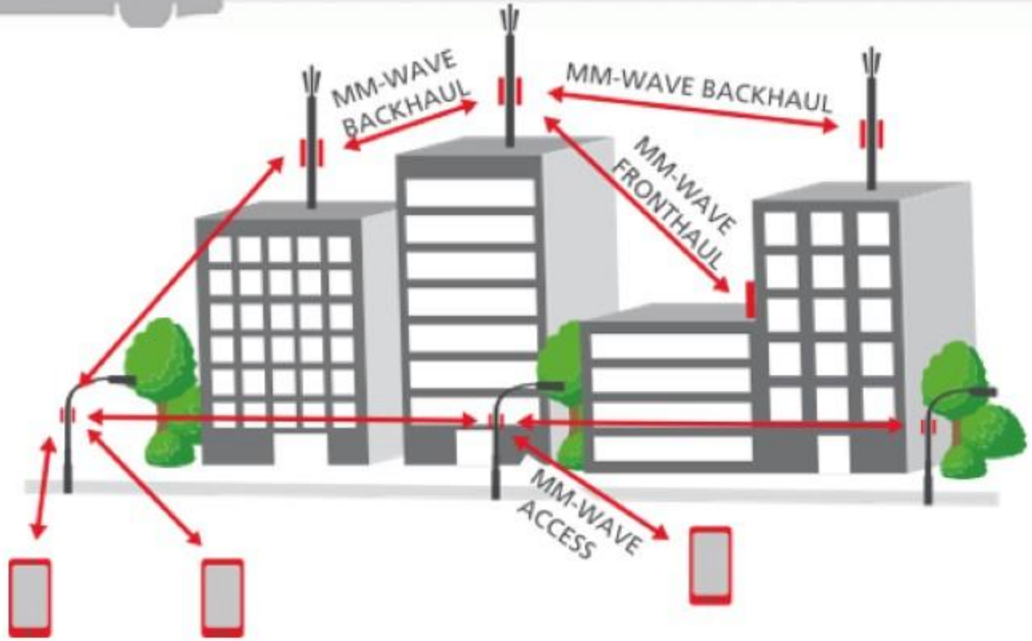
End User

无线回传



BS
AP
4G
Macro Cell
Backhaul
mmW
Small Cell

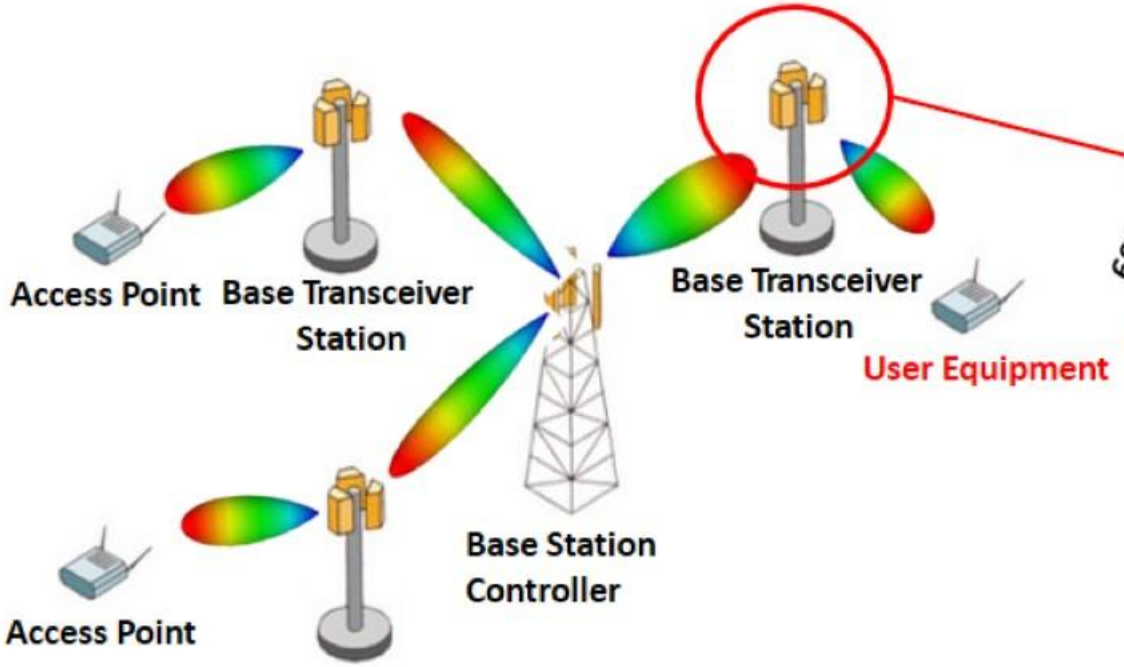


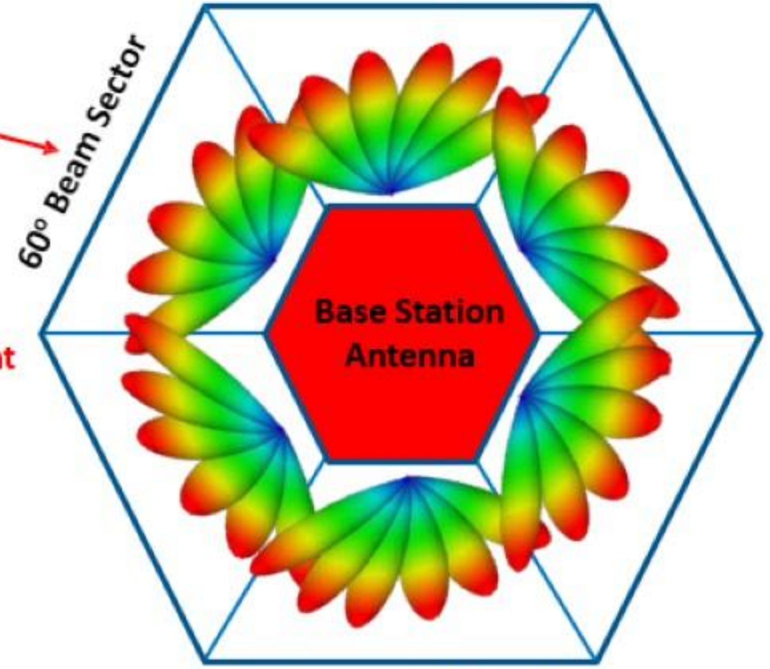


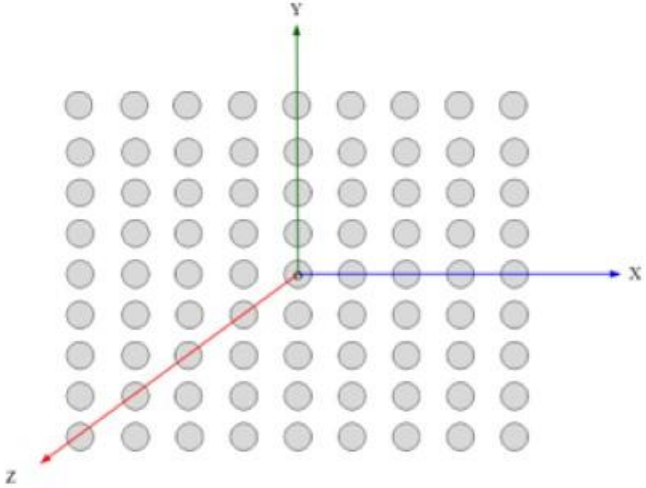
MM-WAVE BACKHAUL
MM-WAVE BACKHAUL
MM-WAVE FRONTHAUL
MM-WAVE ACCESS

基站智能天线

- 智能天线（波束成形）是实现5G 毫米波的关键
- 窄波束通过码本不断切换从而实现不同方向的波束扫描，以实现收发波束对准，并完成5G无线链路连接

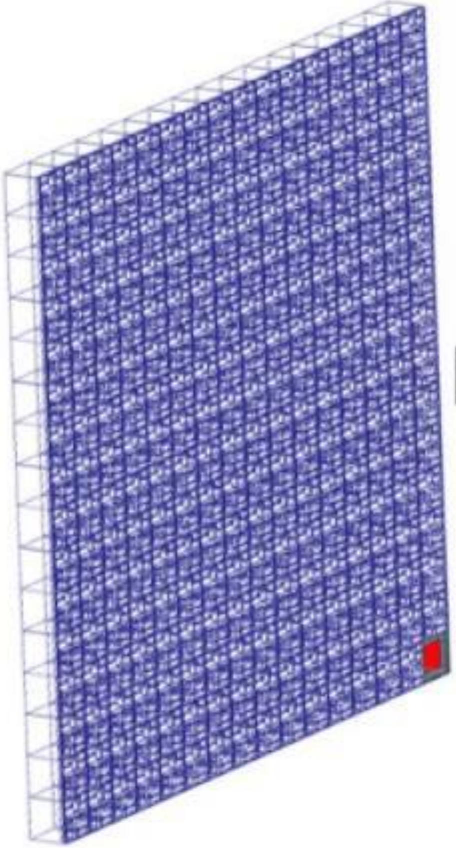




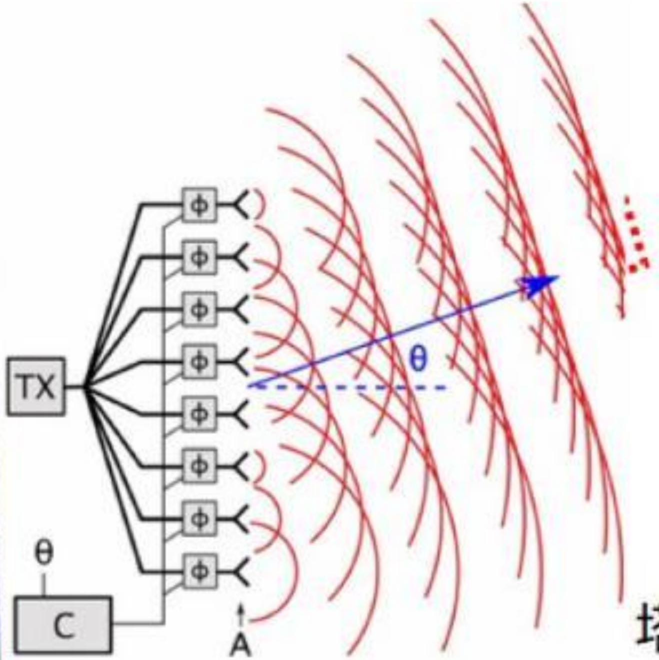


Beams sector in U-V plane

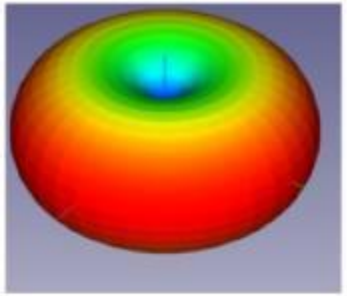
ANSYS 5G Beamforming仿真技术

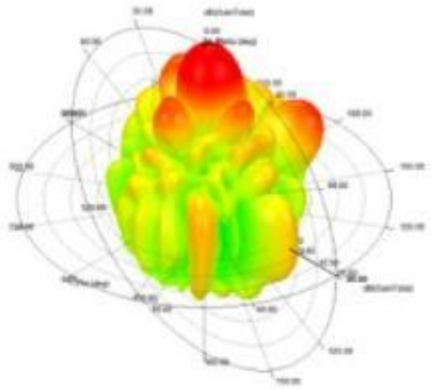


相控阵



塔台



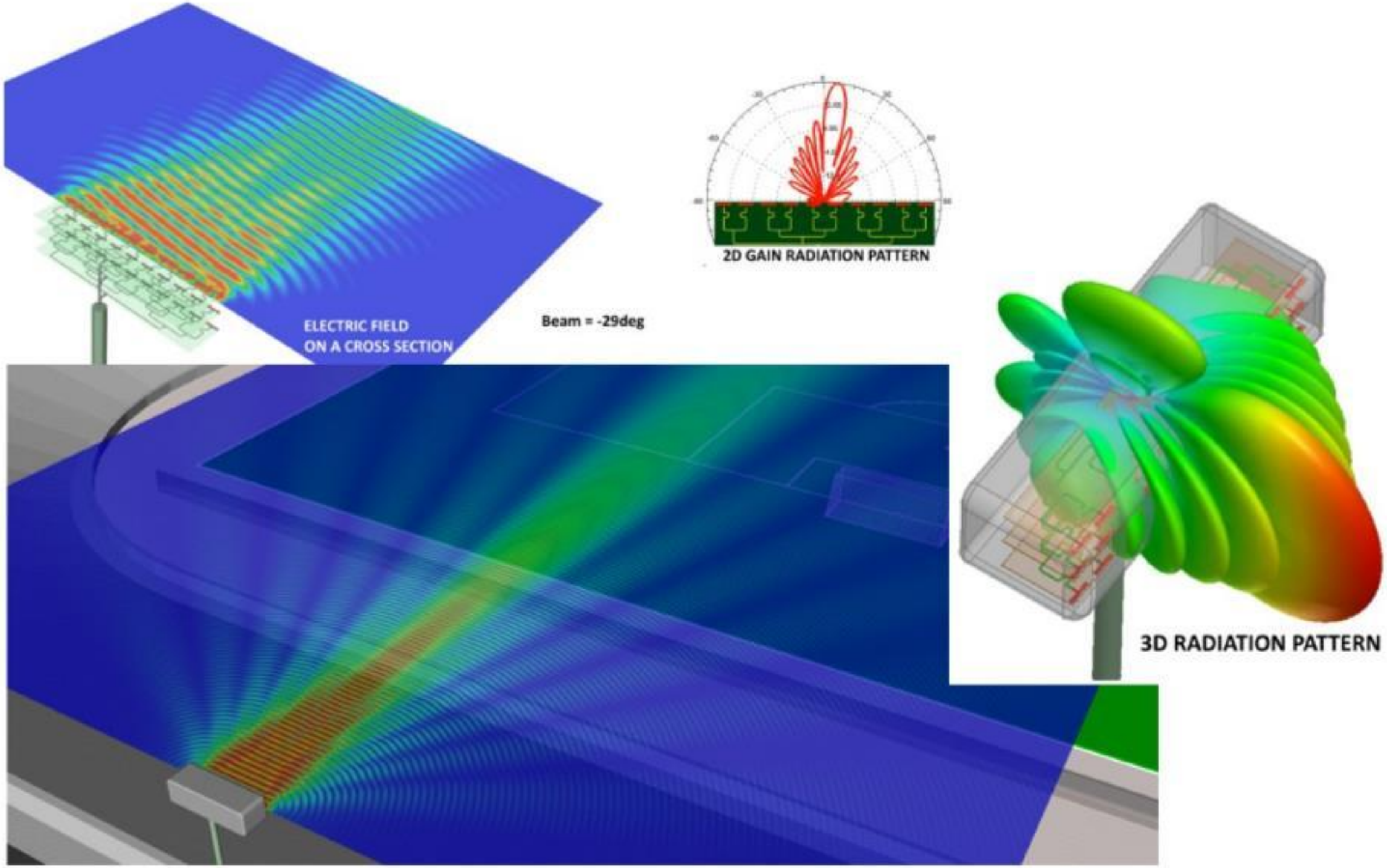


塔台发送信号

✓ 相控阵接收塔台信号的幅度和相位信息
  - 获得信道状态信息

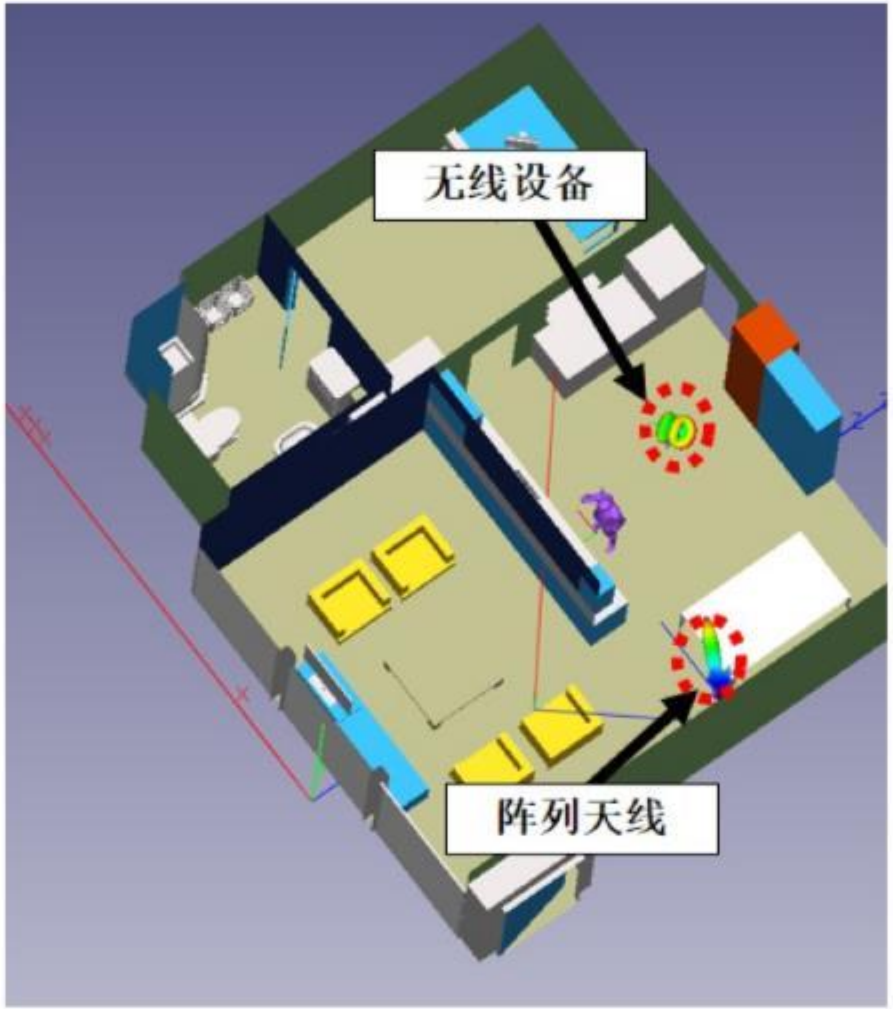
✓ 应用自适应Beamforming算法生成最优波束
  - 共轭Beamforming算法

仿真能力提升 - 热点覆盖

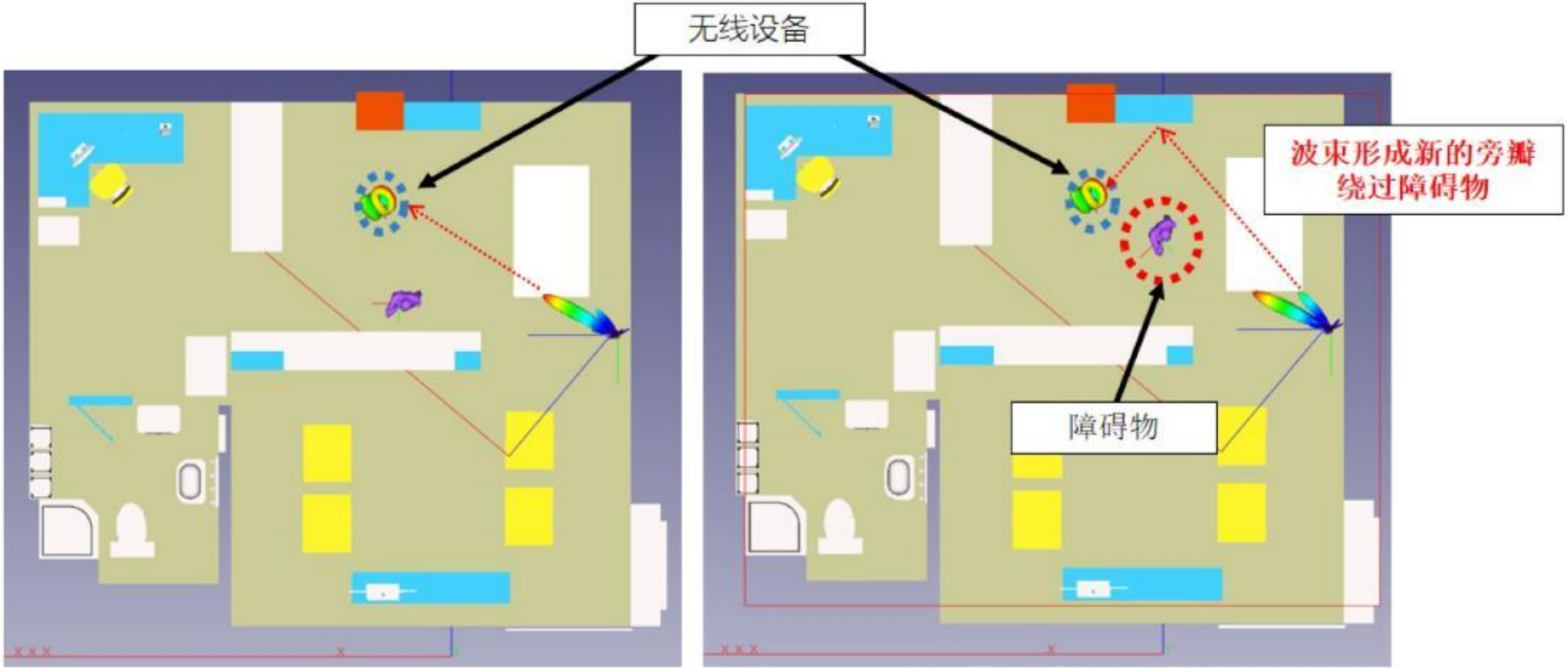

2D GAIN RADIATION PATTERN
ELECTRIC FIELD
ON A CROSS SECTION
Beam = -29deg
3D RADIATION PATTERN

ANSYS 5G Beamforming仿真应用—实际场景分析

- ✓ 复杂散射环境
  - ✓ 介质和金属
- ✓ 阵列天线的**Beamforming**基于设备接收的信道信息来确定
- ✓ 阵列天线的方向图自适应补偿环境变化



ANSYS 5G Beamforming仿真应用—实际场景分析

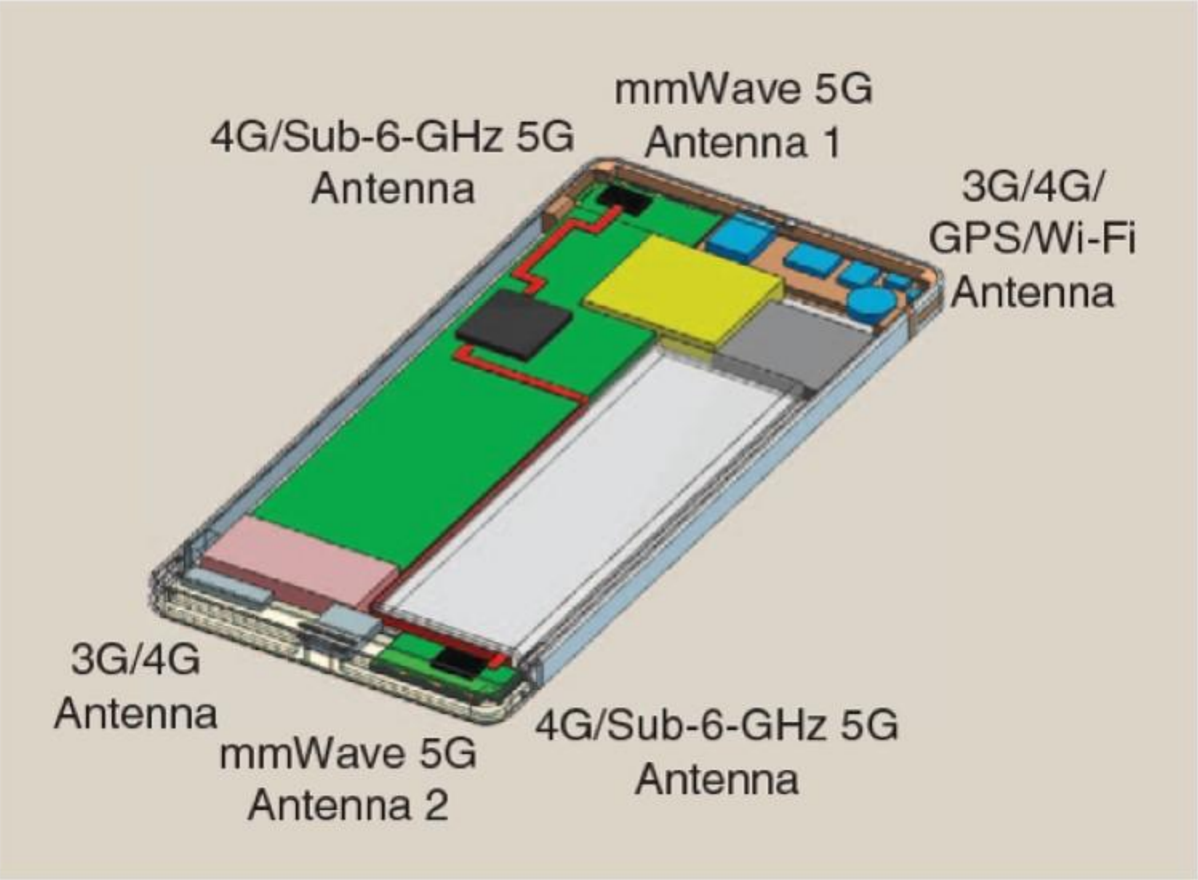


场景一：无遮挡

场景二：部分遮挡

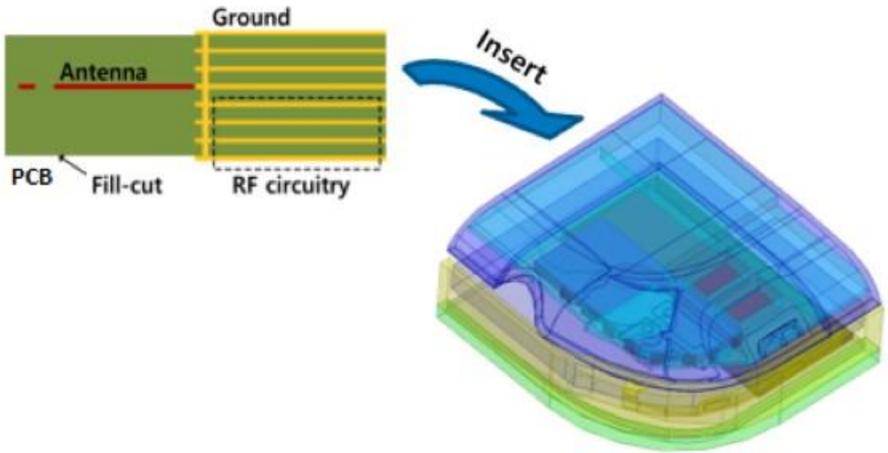
单个设备应用

5G在移动终端的应用



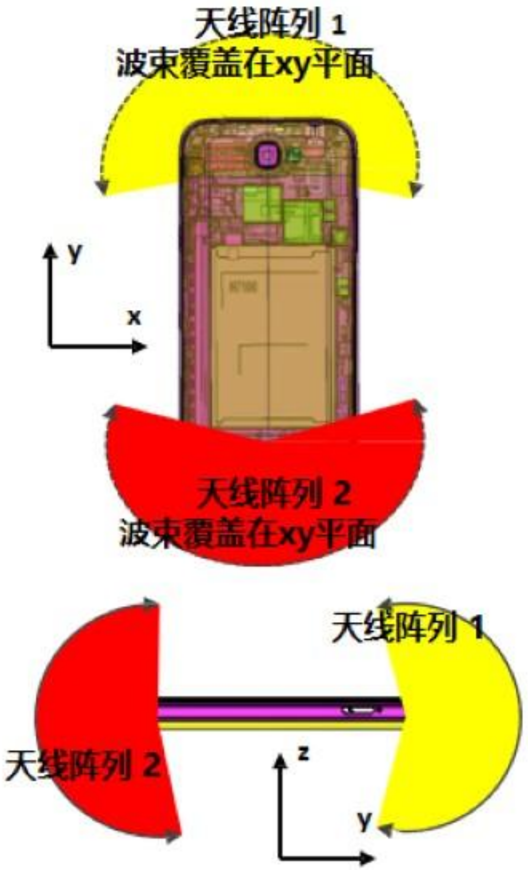
Conditions

- Multiple bands(LTE/sub-6G/mm-wave) antenna coexistence
- The array antenna has broadside and end-fire beam
- 5G antenna module is located around top, bottom or corner of mobile devices.
- The PCB substrate is low loss & low Dk dielectric
- Complex surrounding like chassis or case



封装天线模块在移动终端的应用

宽覆盖

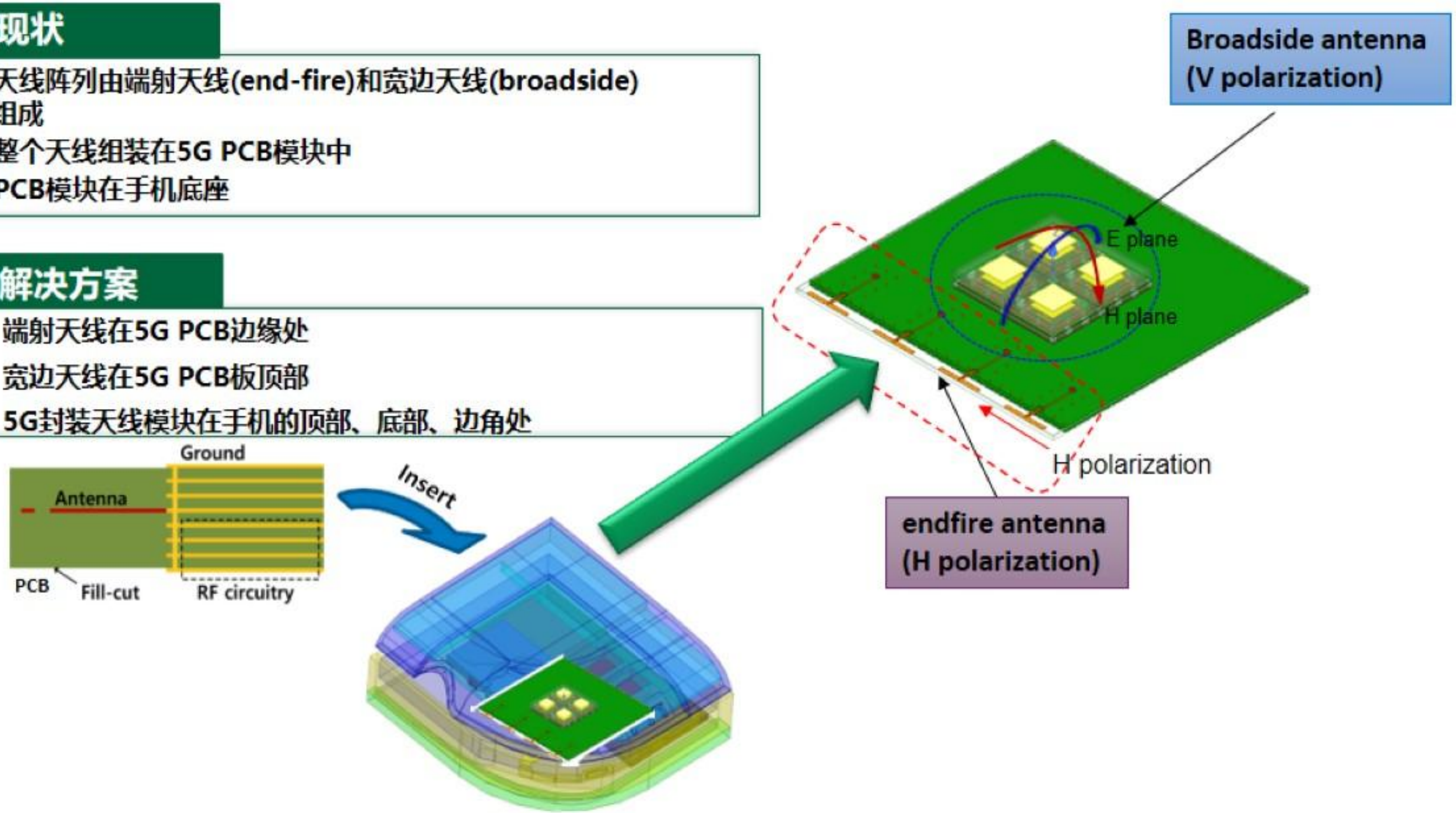


现状

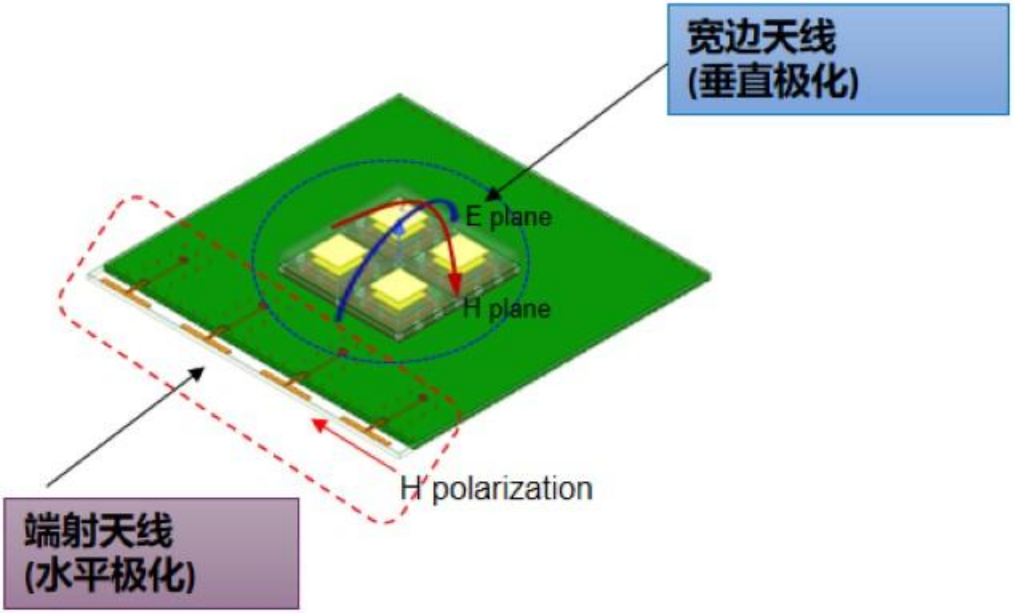
- 天线阵列由端射天线(end-fire)和宽边天线(broadside)组成
- 整个天线组装在5G PCB模块中
- PCB模块在手机底座

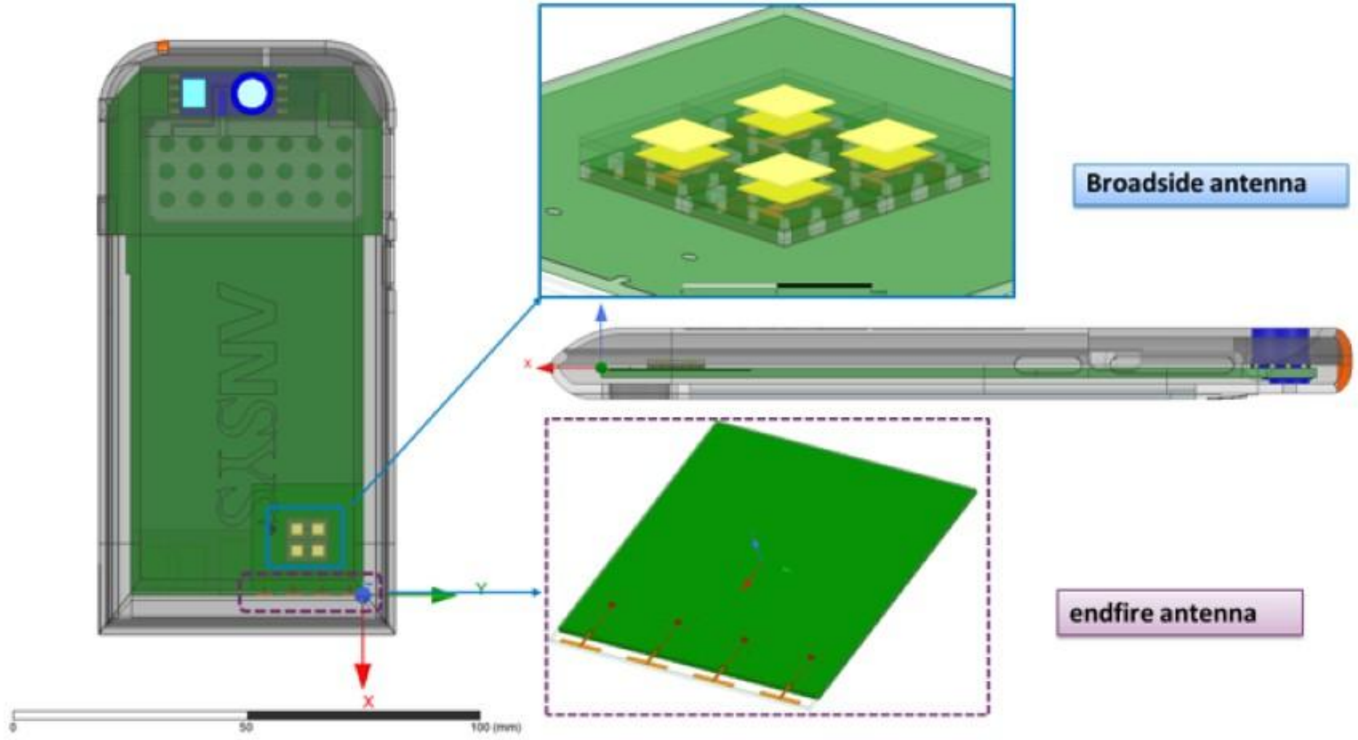
解决方案

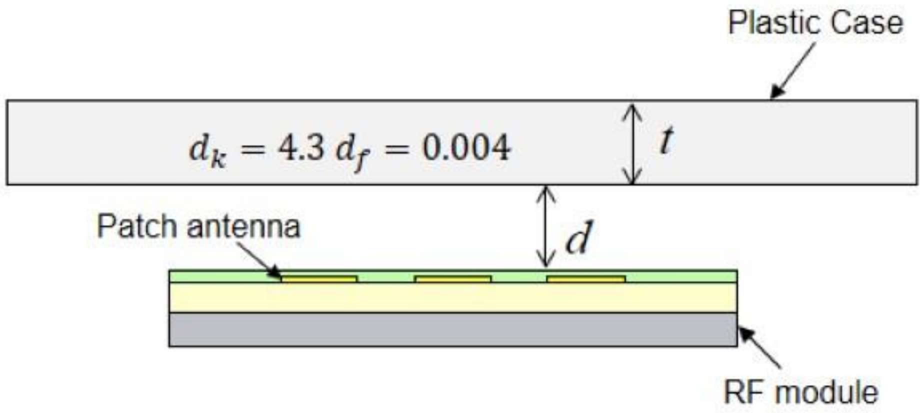
- 端射天线在5G PCB边缘处
- 宽边天线在5G PCB板顶部
- 5G封装天线模块在手机的顶部、底部、边角处

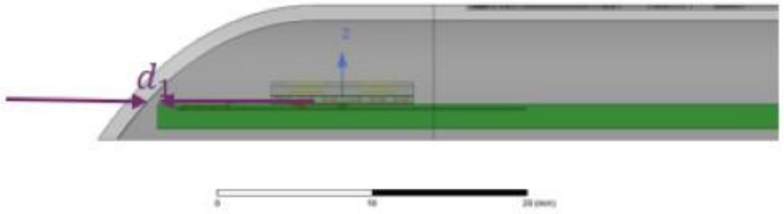


封装天线在移动终端的应用



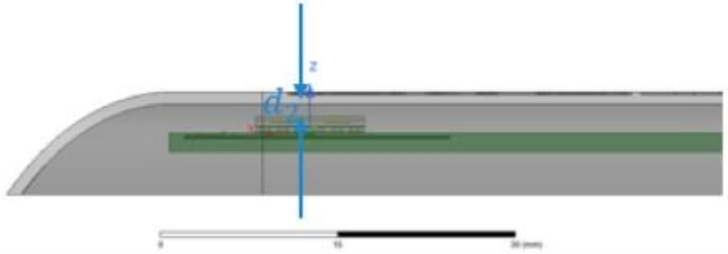




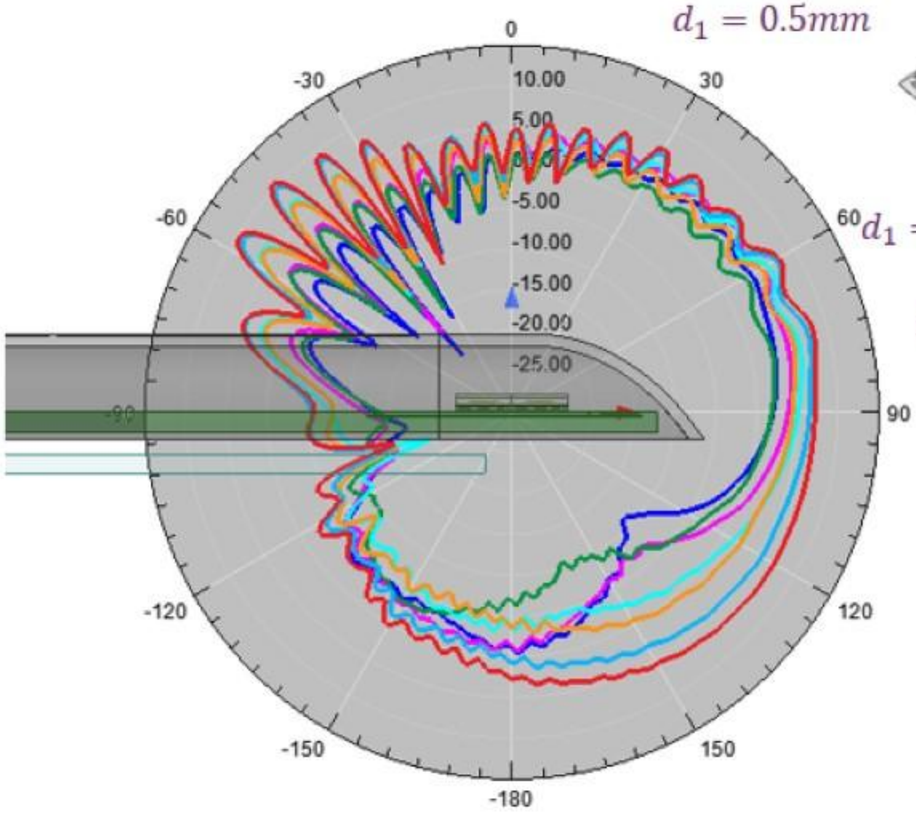


塑壳与端射天线间距敏感度分析

塑壳与宽边天线间距敏感度分析



手机机壳影响 - 端射天线



$d_1 = 0.5mm$

$d_1 = 1.0mm$

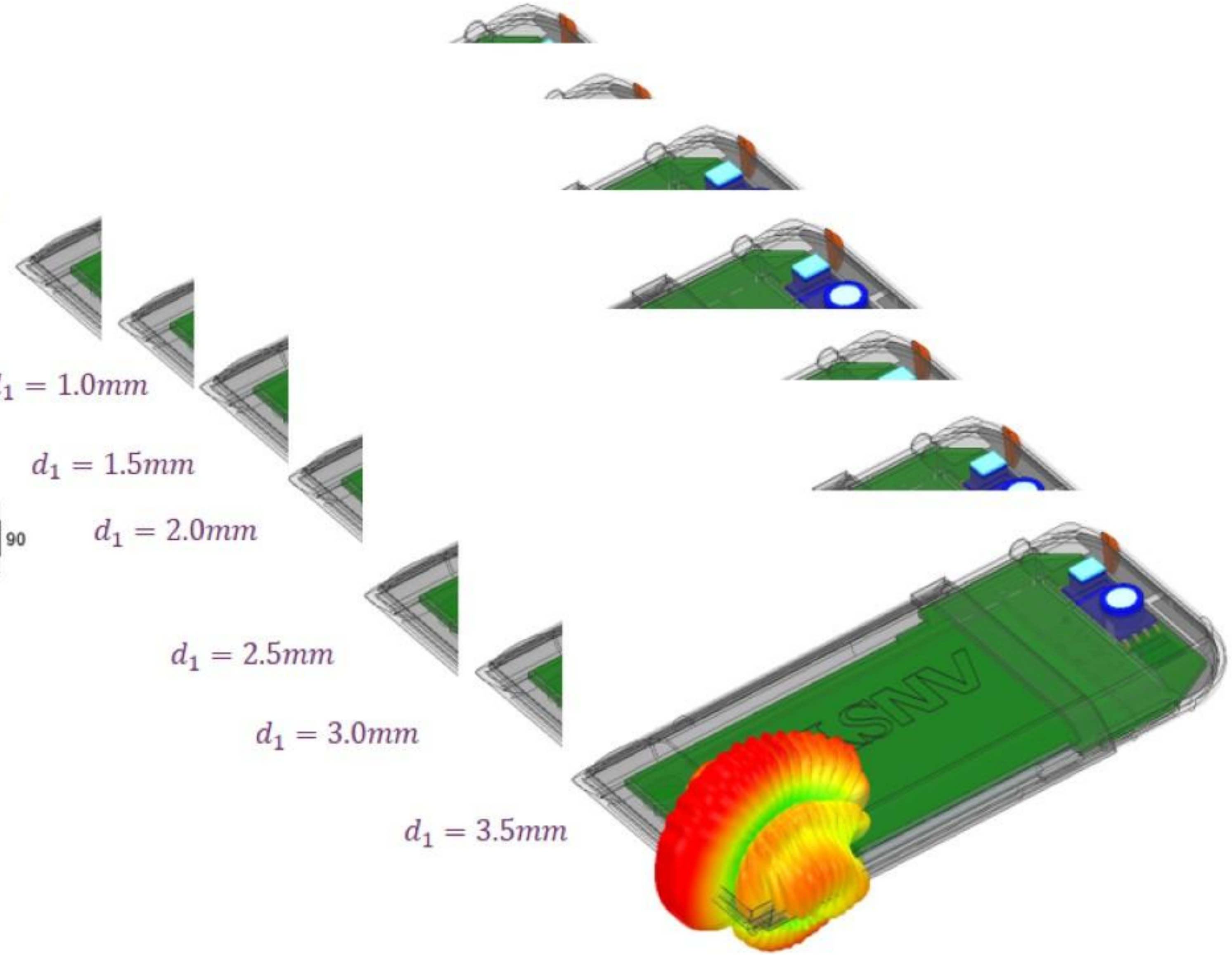
$d_1 = 1.5mm$

$d_1 = 2.0mm$

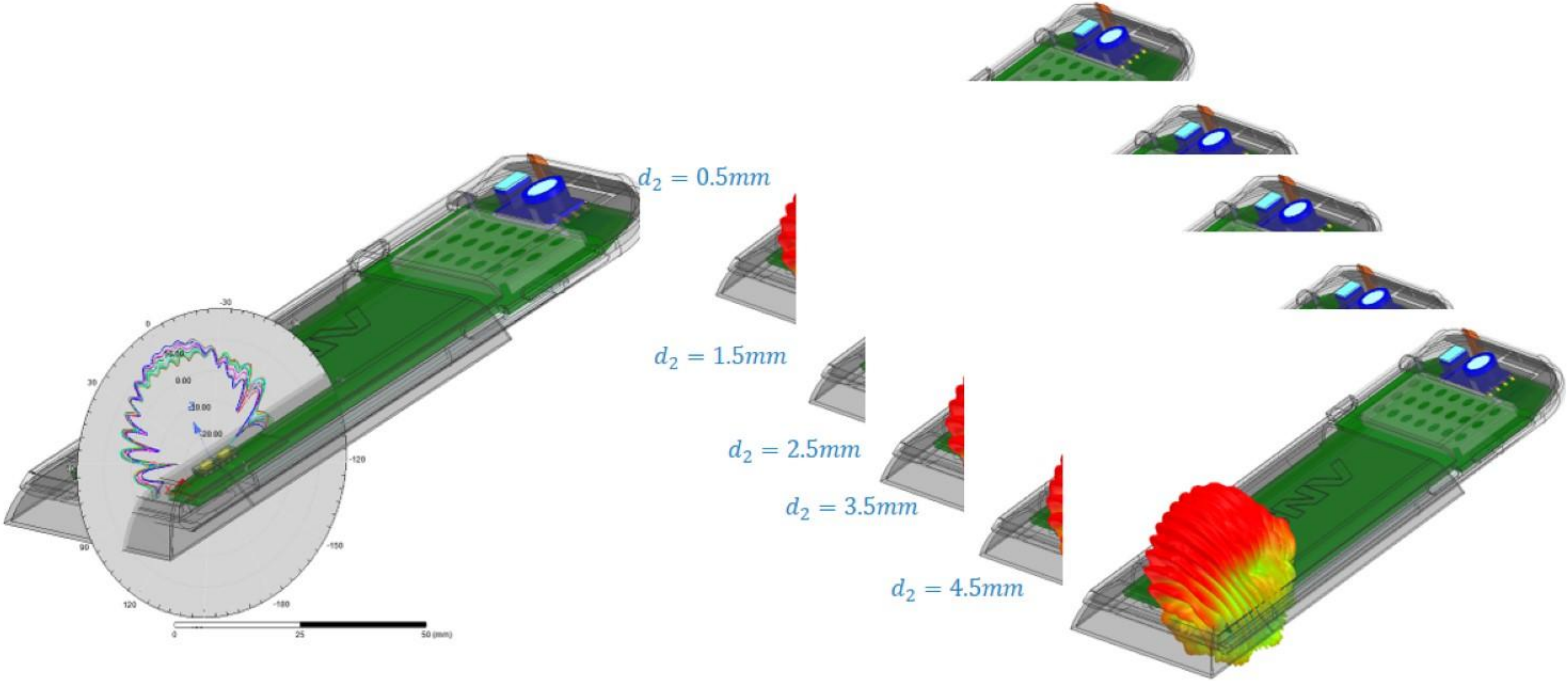
$d_1 = 2.5mm$

$d_1 = 3.0mm$

$d_1 = 3.5mm$

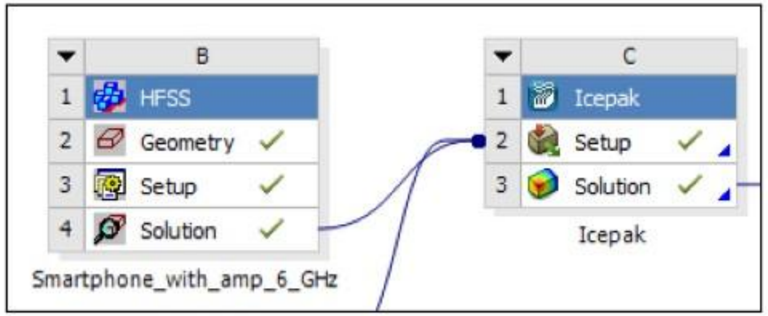


手机机壳影响 - 宽边天线



ANSYS HFSS → Icepak 双向耦合分析

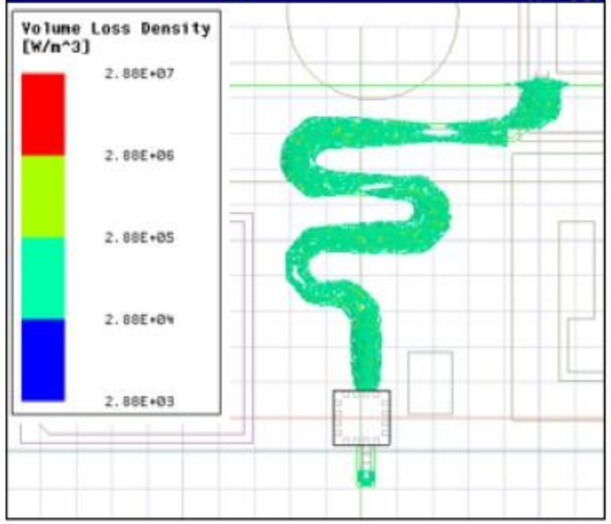
- 通过ANSYS Workbench实现从ANSYS HFSS传输到ANSYS Icepak中的天线金属损耗及介质损耗



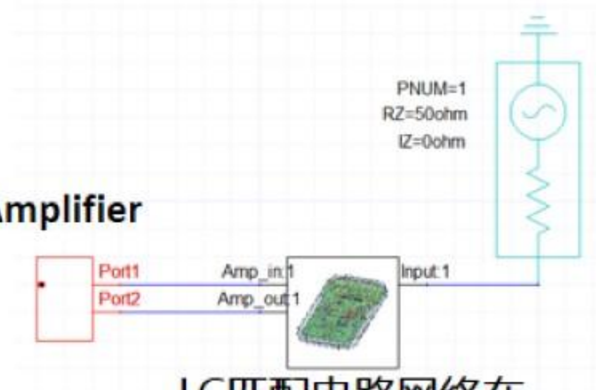
Total RF heat load ~ 8 mW

- **PCB: 6 mW**
- **Metals: ~ 2 mW**

不足以影响温度

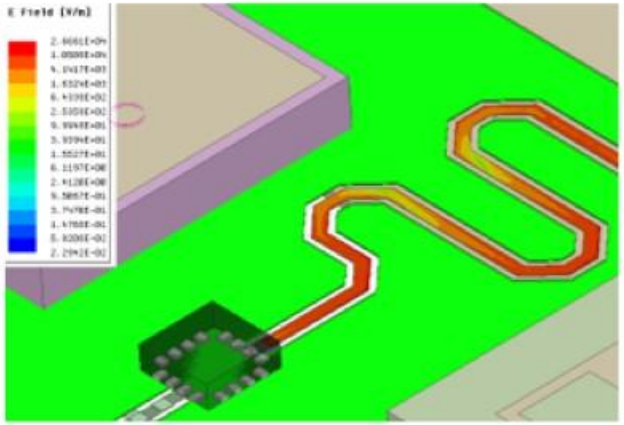


Amplifier



LC匹配电路网络在HFSS模型搭建

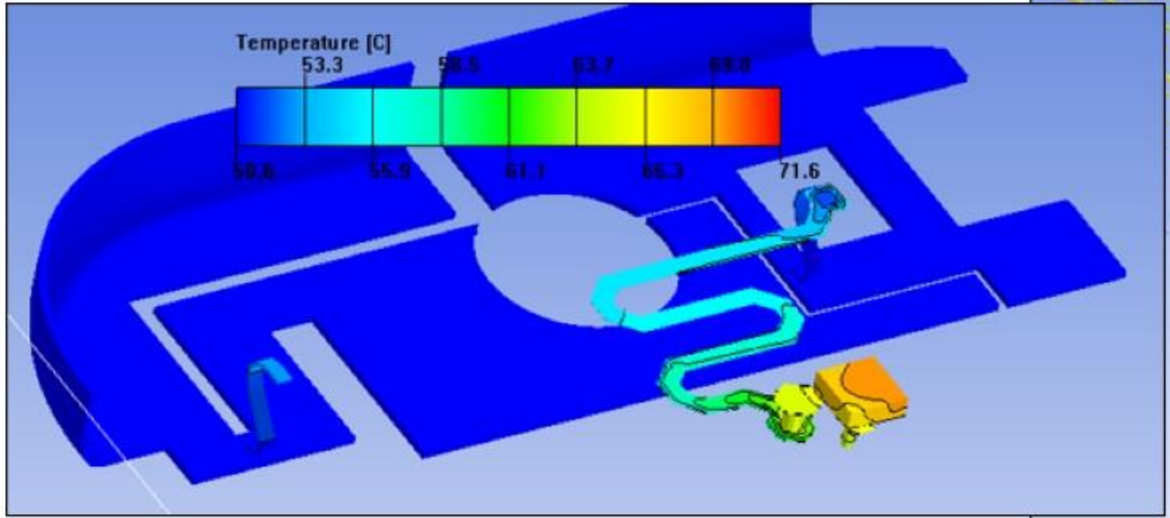
RF source controls input power level

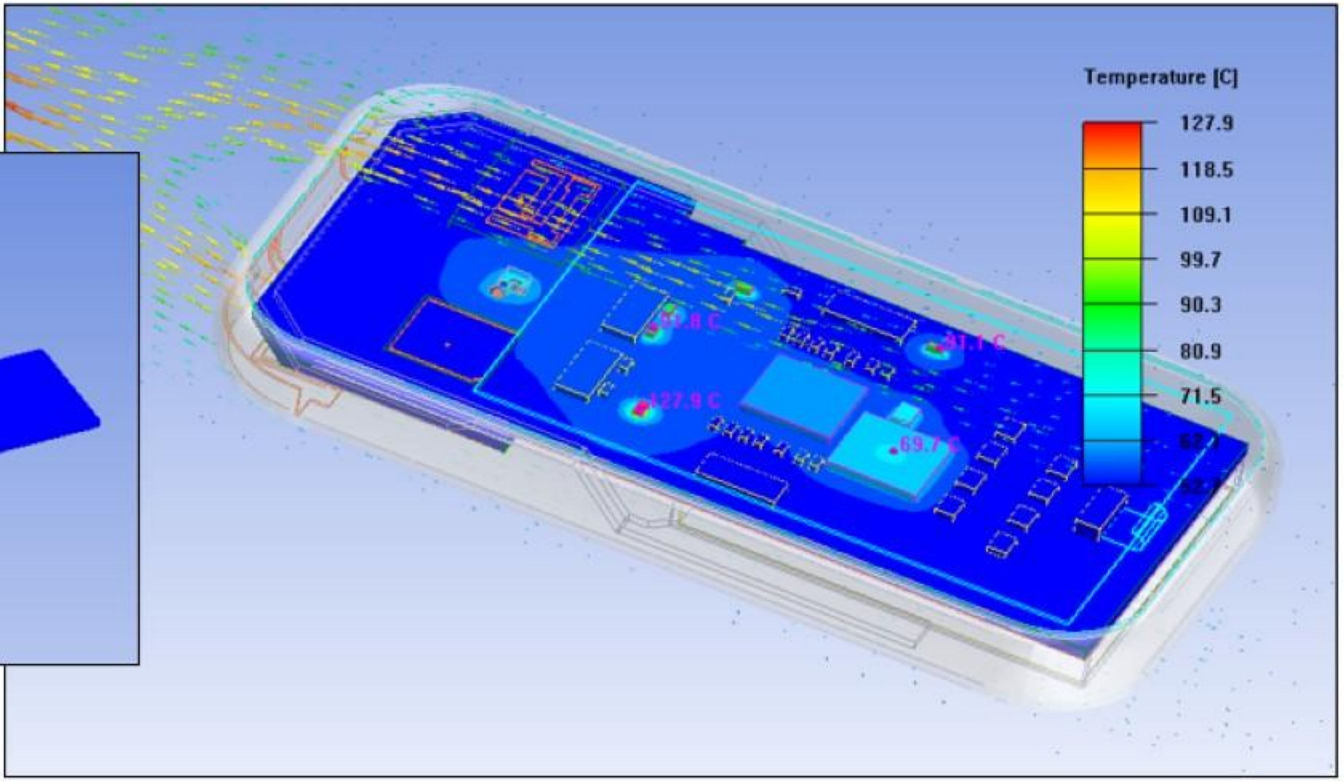


"路到场"推送计算实际的热功率损耗密度

ANSYS HFSS → Icepak 双向耦合分析

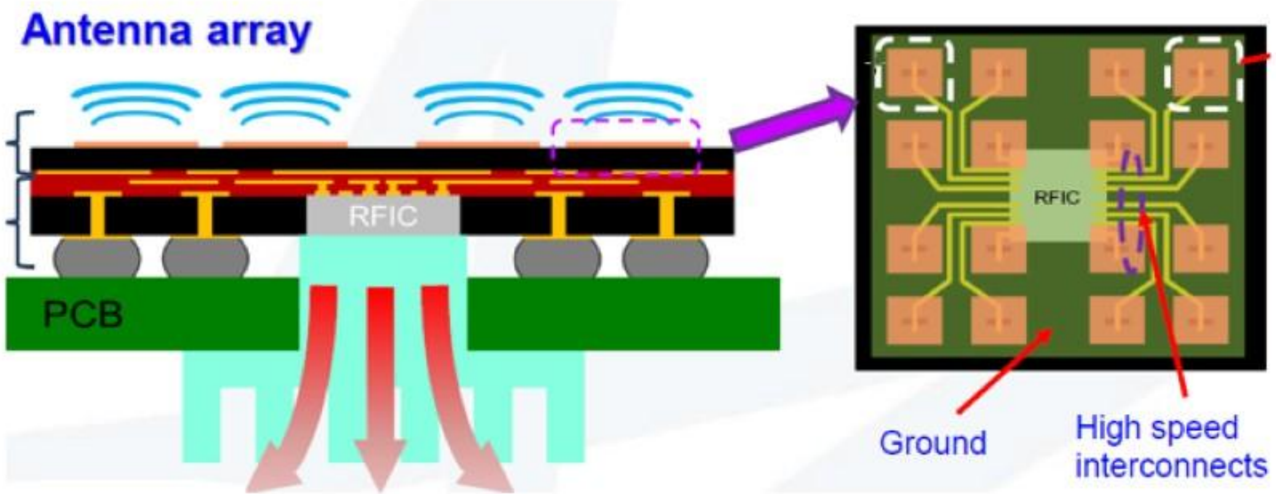
- 导入PCB组件的介质损耗>> RF Loads: Total = 1.217 W
  - 由于PCB组件的温度升高，RF /天线性能会受到影响
- 热条件:
  - 环境温度45°C
  - 辐射传热 On



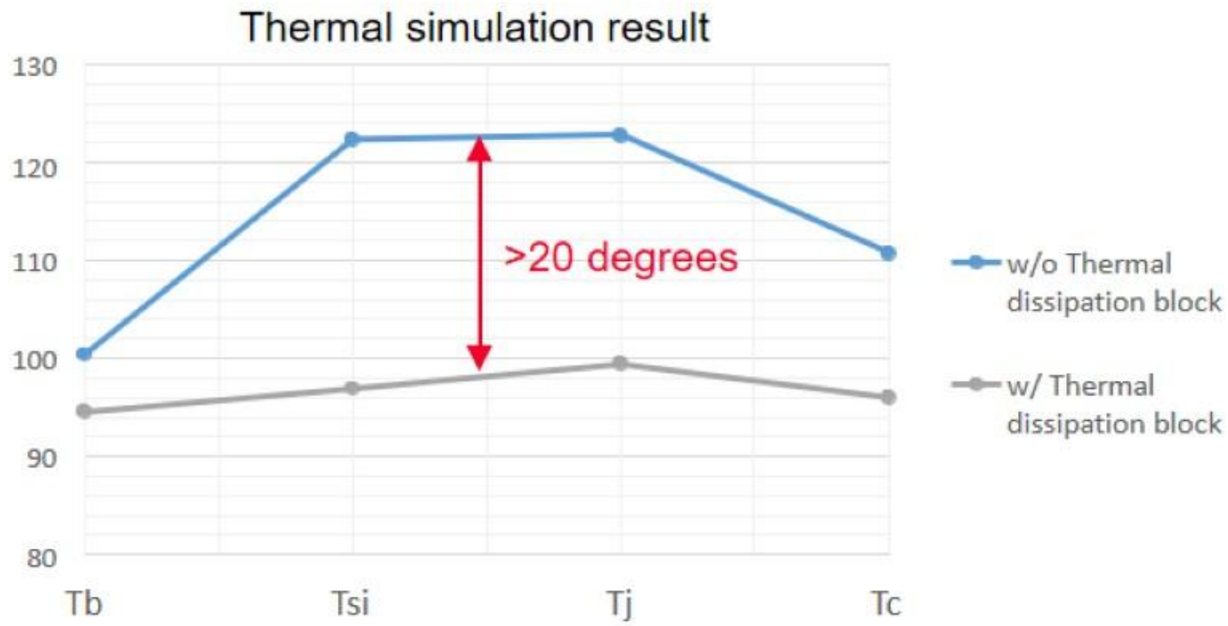


- 仿真结果:
  - RF放大器结温: **71.6 °C**
  - 天线加通道温度: **53 °C to 70 °C**

散热设计

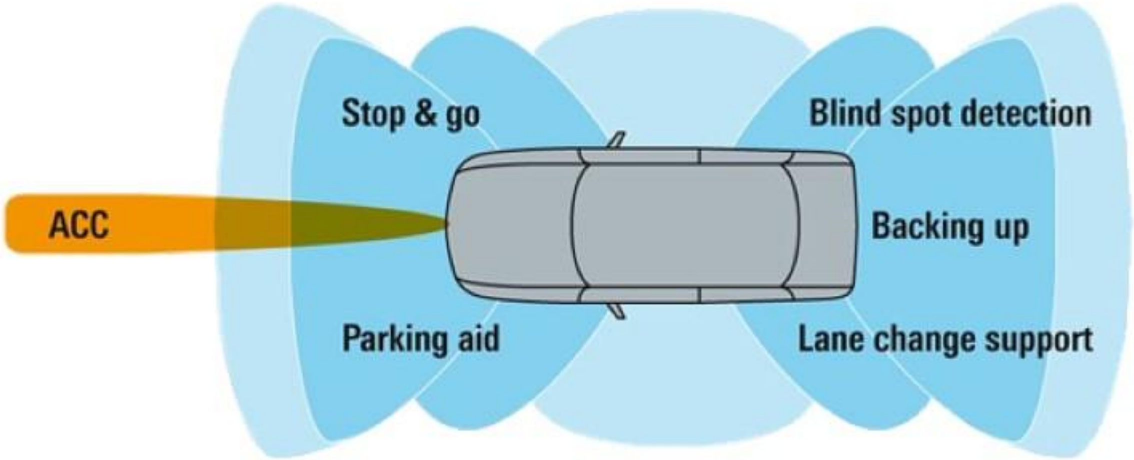


Antenna array
RFIC
PCB
RFIC
Ground
High speed interconnects



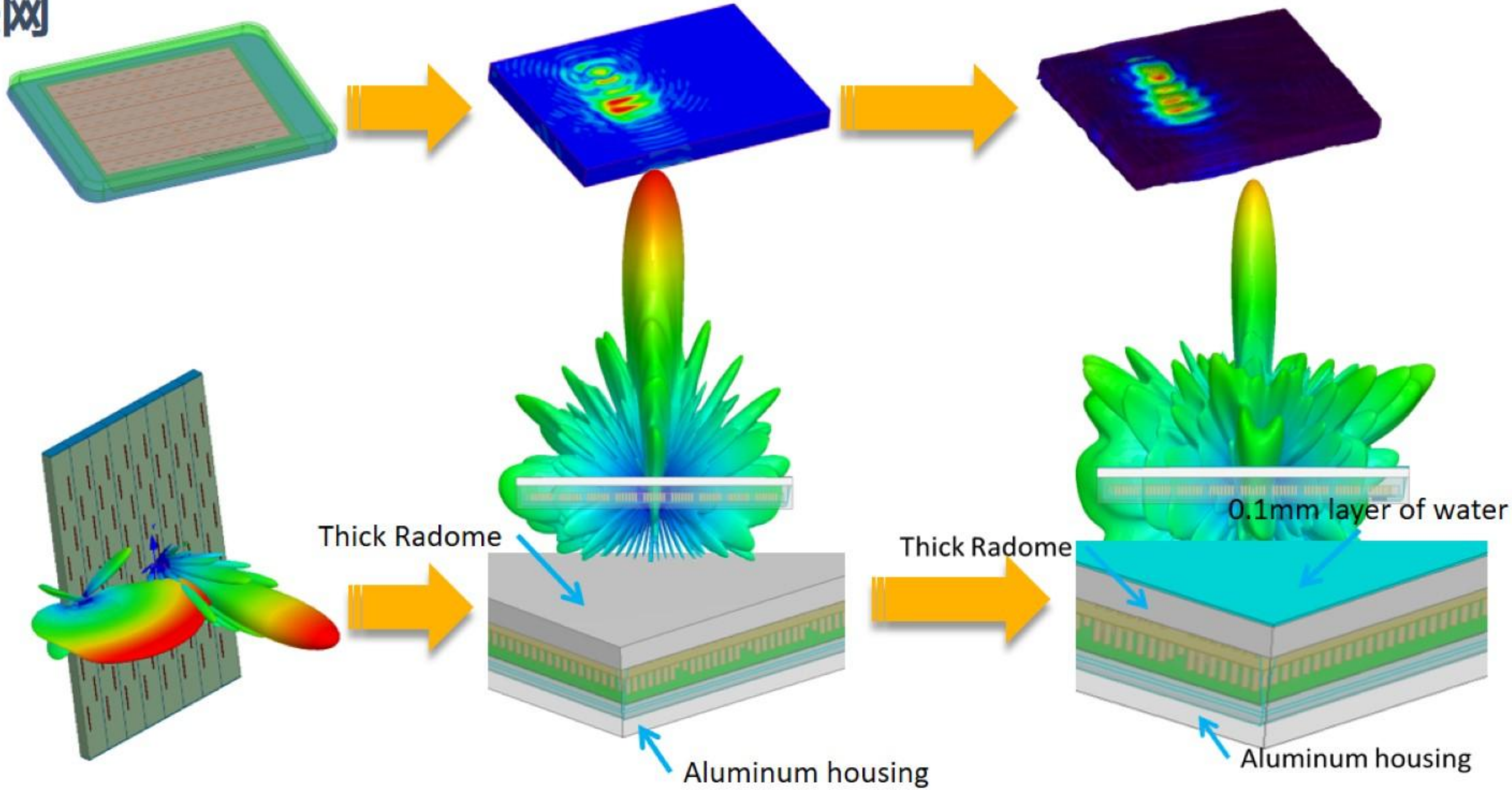
Thermal simulation result
130
120
110
100
90
80
>20 degrees
Tb
Tsi
Tj
Tc
w/o Thermal dissipation block
w/ Thermal dissipation block

车联网



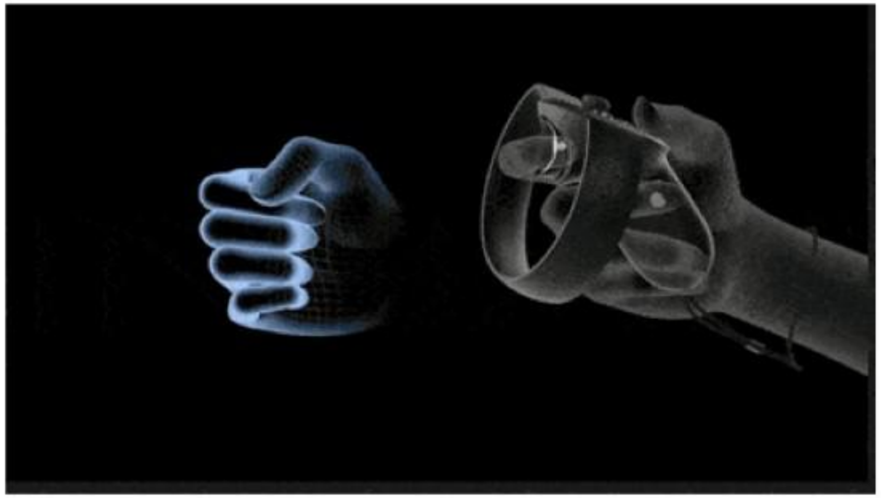
Collision warning
Collision mitigation
Stop & go
Blind spot detection
ACC
Backing up
Parking aid
Lane change support
Precrash

车联网

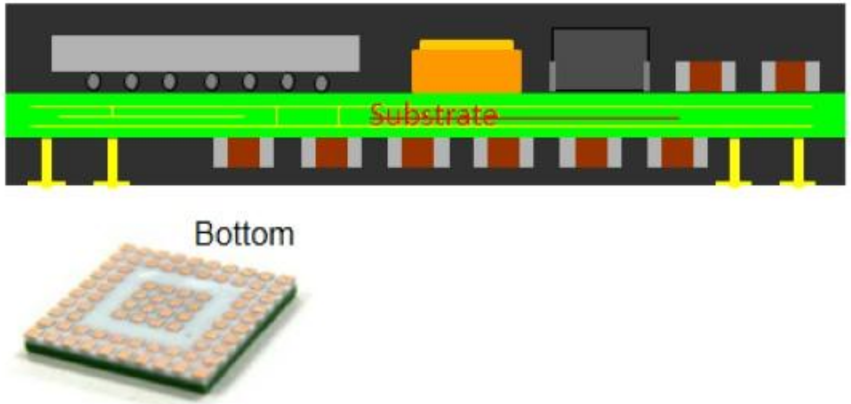


Thick Radome
Aluminum housing
Thick Radome
0.1mm layer of water
Aluminum housing

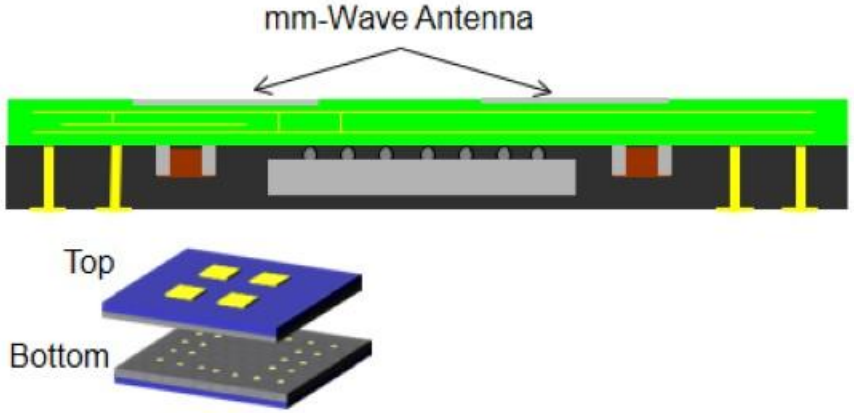
VR AR 手势识别技术



微波模块 vs 毫米波模块



微波模块结构



毫米波模块结构

- 射频通道与天线独立
- 传导测试
- 塑壳影响小
- 传统基板

核心技术

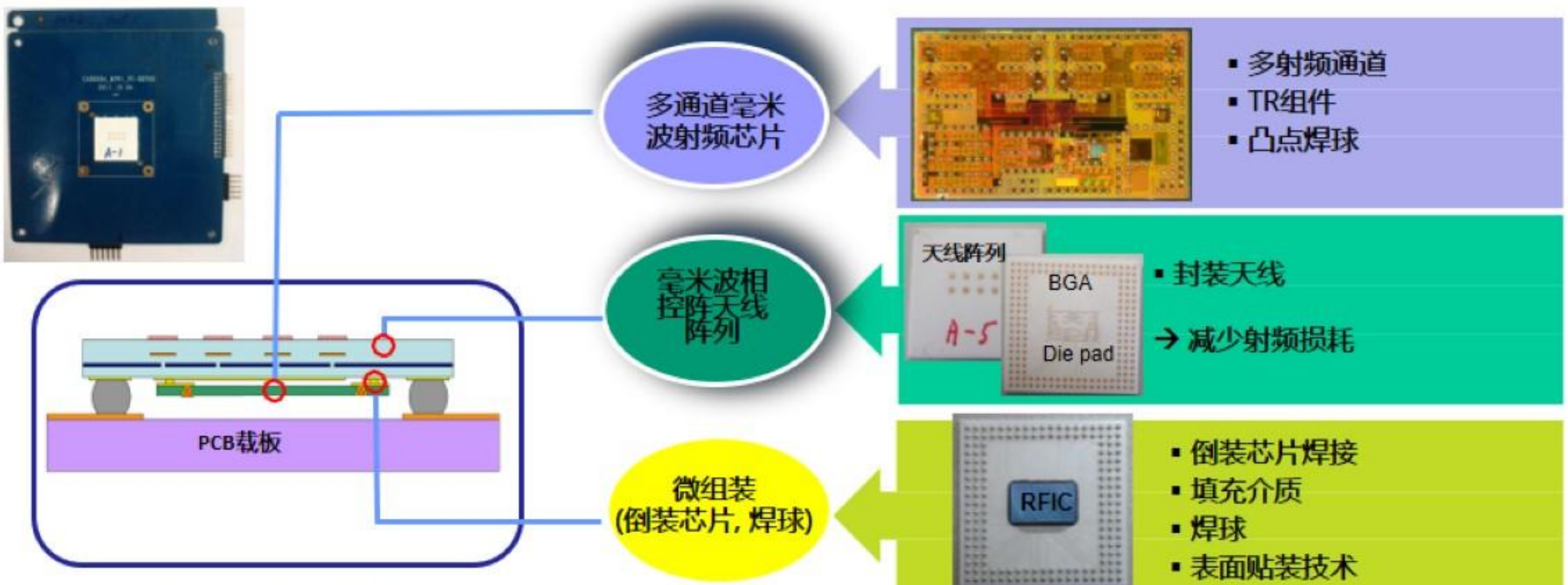
- 小型高性能射频设备
- 高频电路设计
- 小而薄的封装

- 与天线阵列集成
- 自由空间辐射测试
- 塑壳影响大
- 低损耗基板

核心技术

- 毫米波材料
- 天线阵列设计
- 封装天线设计
- 毫米波射频馈线

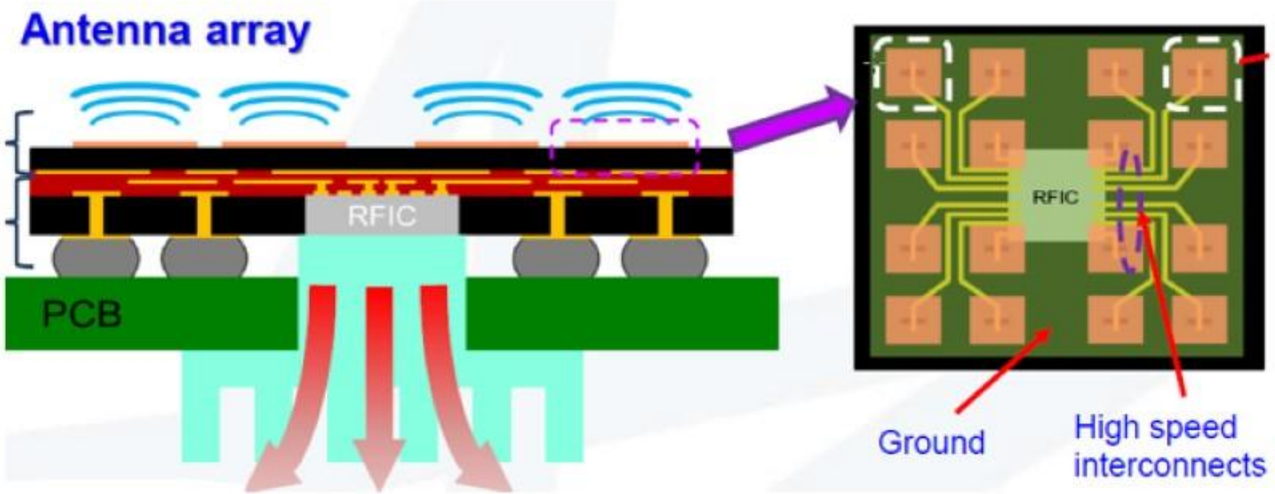
5G 毫米波智能天线模块



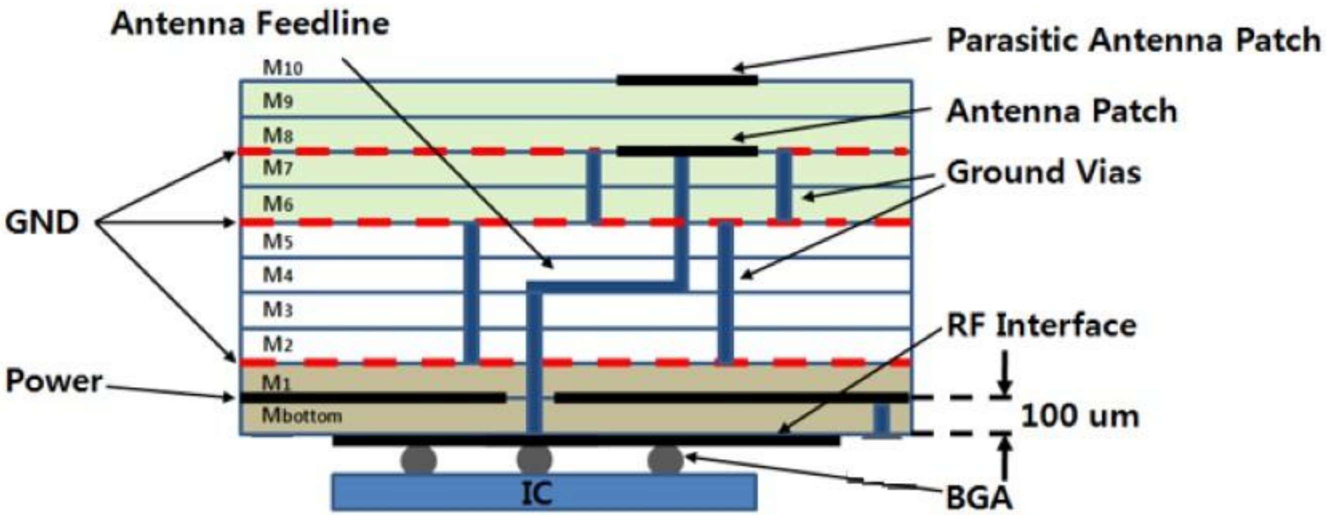
5G毫米波封装天线模块

AIP vs AoB

AIP

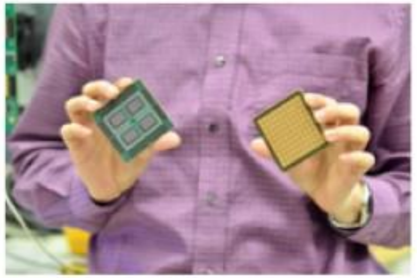


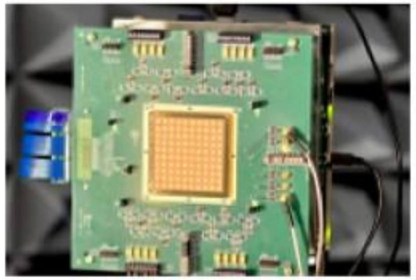
AoB

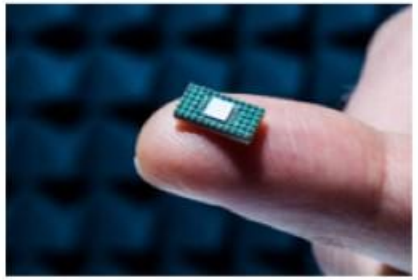


AIP & AoB 设计

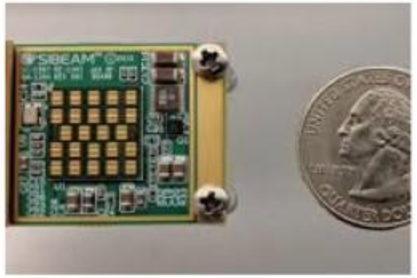
AIP

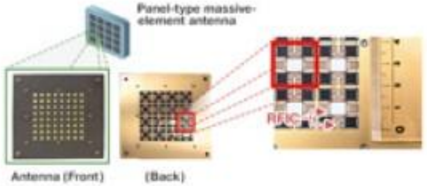


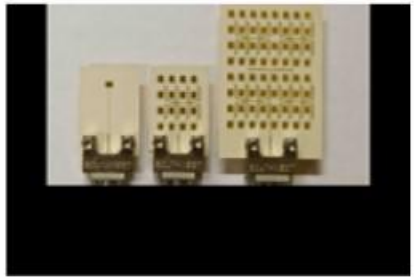




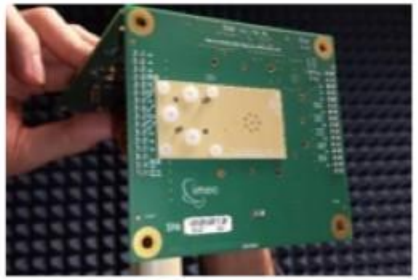
AoB

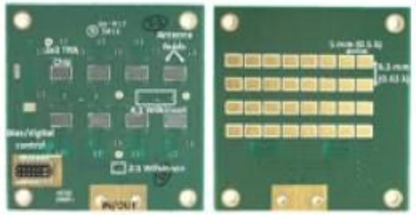


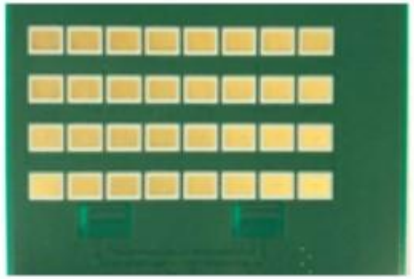


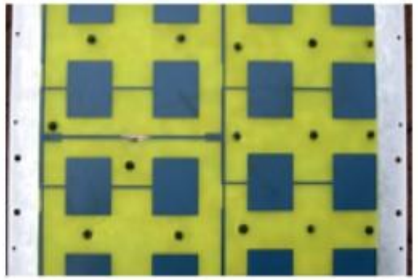


AoB

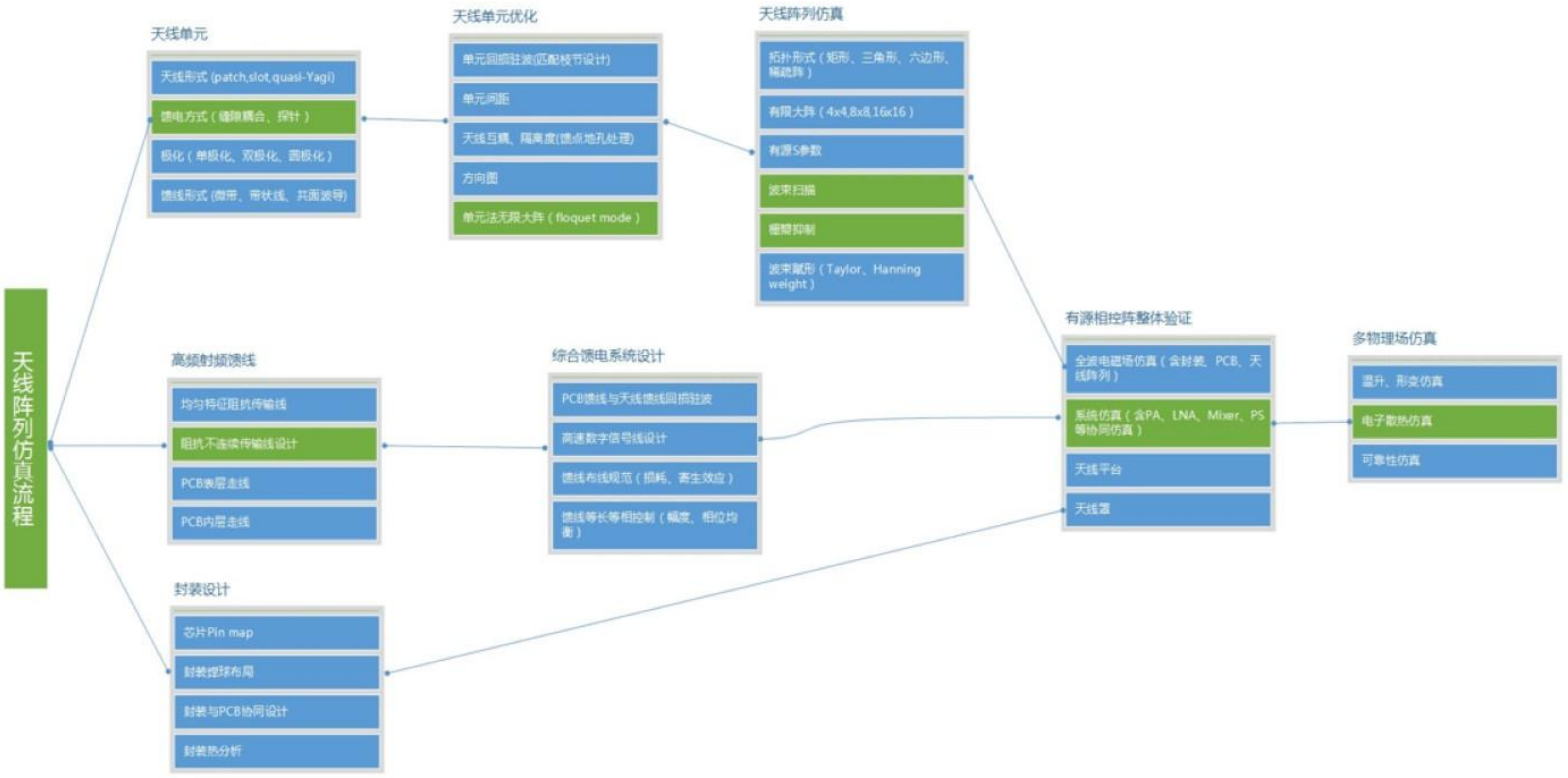






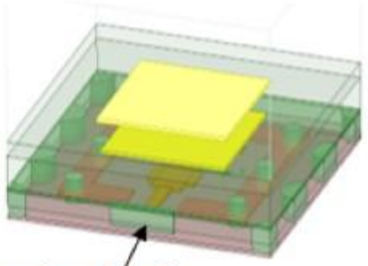


ANSYS 5G天线系统设计流程

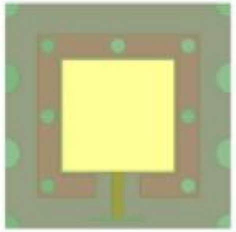


1.毫米波天线单元设计

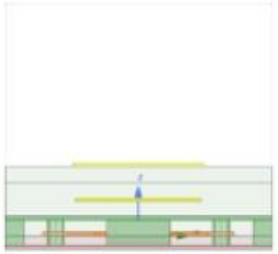
设计步骤1：参数化建模



Overview of antenna unit

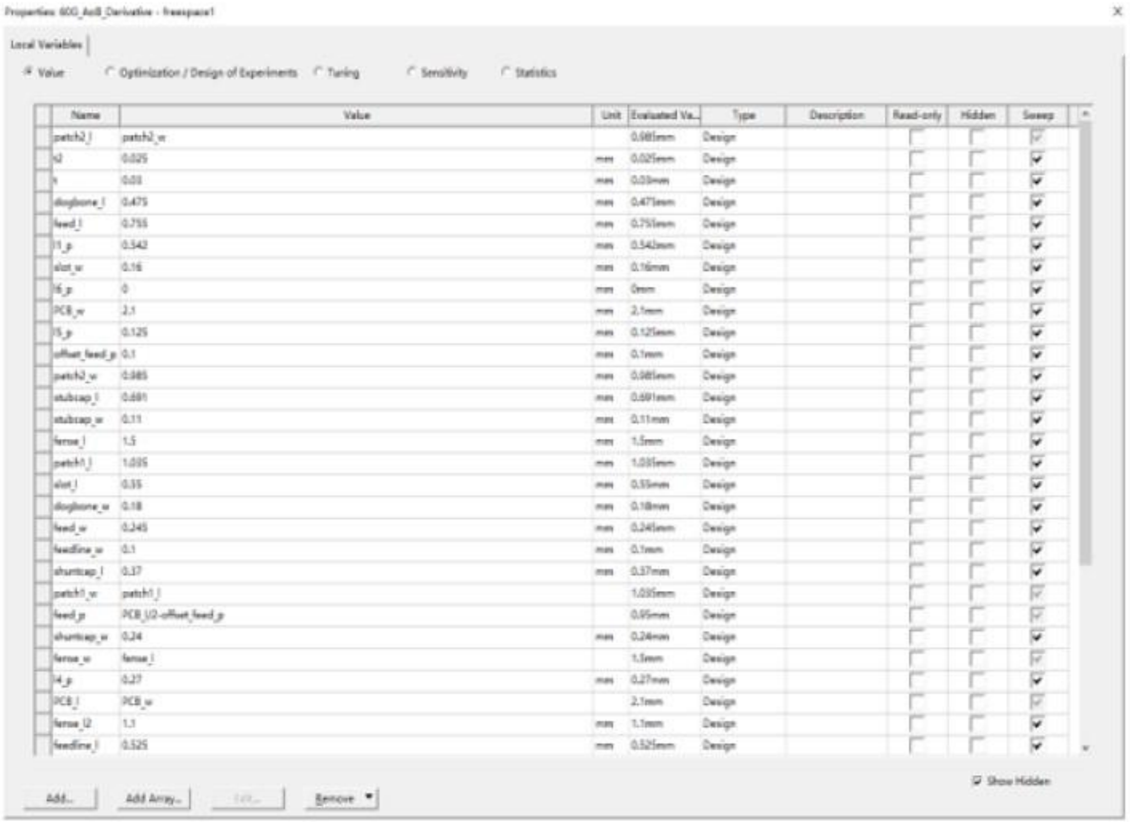


Top view of Geometry



Stackup layers for antenna and PCB

天线单元模型



Name	Value	Unit	Evaluated Va...	Type
patch2_l	patch2_w		0.985mm	Design
h2	0.025	mm	0.025mm	Design
h	0.03	mm	0.03mm	Design
dogbone_l	0.475	mm	0.475mm	Design
feed_l	0.755	mm	0.755mm	Design
l1_p	0.542	mm	0.542mm	Design
slot_w	0.16	mm	0.16mm	Design
l6_p	0	mm	0mm	Design
PCB_w	2.1	mm	2.1mm	Design
l5_p	0.125	mm	0.125mm	Design
offset_feed_p	0.1	mm	0.1mm	Design
patch2_w	0.985	mm	0.985mm	Design
stubcap_l	0.691	mm	0.691mm	Design
stubcap_w	0.11	mm	0.11mm	Design
fense_l	1.5	mm	1.5mm	Design
patch1_l	1.035	mm	1.035mm	Design
slot_l	0.35	mm	0.35mm	Design
dogbone_w	0.18	mm	0.18mm	Design
feed_w	0.245	mm	0.245mm	Design
feedline_w	0.1	mm	0.1mm	Design
shuntcap_l	0.37	mm	0.37mm	Design
patch1_w	patch1_l		1.035mm	Design
feed_p	PCB_l/2-offset_feed_p		0.95mm	Design
shuntcap_w	0.24	mm	0.24mm	Design
fense_w	fense_l		1.5mm	Design
l4_p	0.27	mm	0.27mm	Design
PCB_l	PCB_w		2.1mm	Design
fense_l2	1.1	mm	1.1mm	Design
feedline_l	0.525	mm	0.525mm	Design

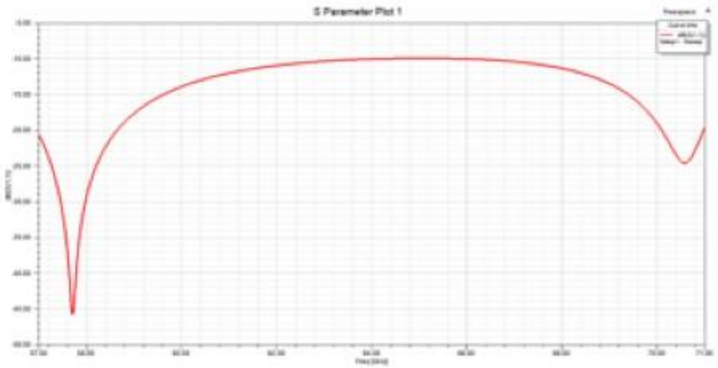
参数化建模

Name	Type	Material	Dielectric Fill	Property
layer 1	Metal	copper	PP	patch
layer 2	dielectric	PP		
layer 3	dielectric	PP		
layer 4	Metal	copper	PP	patch
layer 5	dielectric	Core		
layer 6	Metal	copper	PP	Ground
layer 7	dielectric	PP		
layer 8	Metal	copper	PP	Strip line
layer 9	dielectric	PP		
layer 10	Metal	copper	PP	Ground

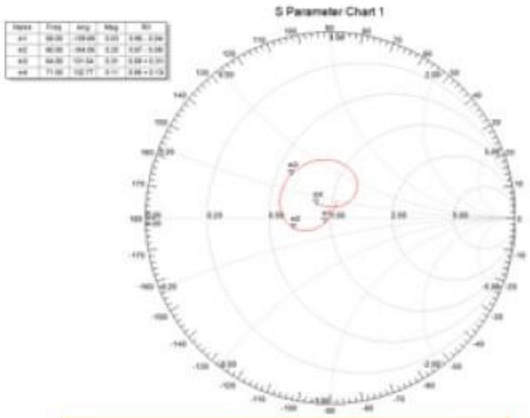
天线叠层结构

- 10层 HDI PCB工艺
- 天线单元采用缝隙耦合馈电方式
- 双叠层patch天线增加带宽
- 天线间距为1/2最高频率波长

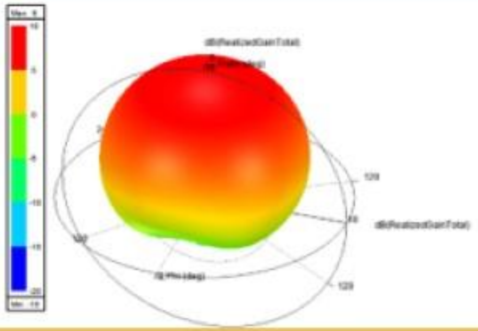
设计步骤2: 天线单元在自由空间性能



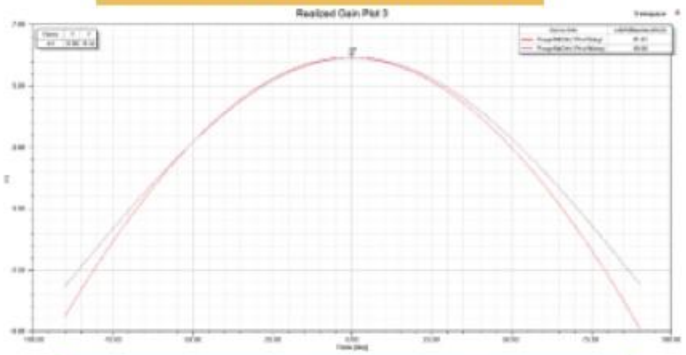
Return Loss of antenna unit



Smith chart of antenna unit



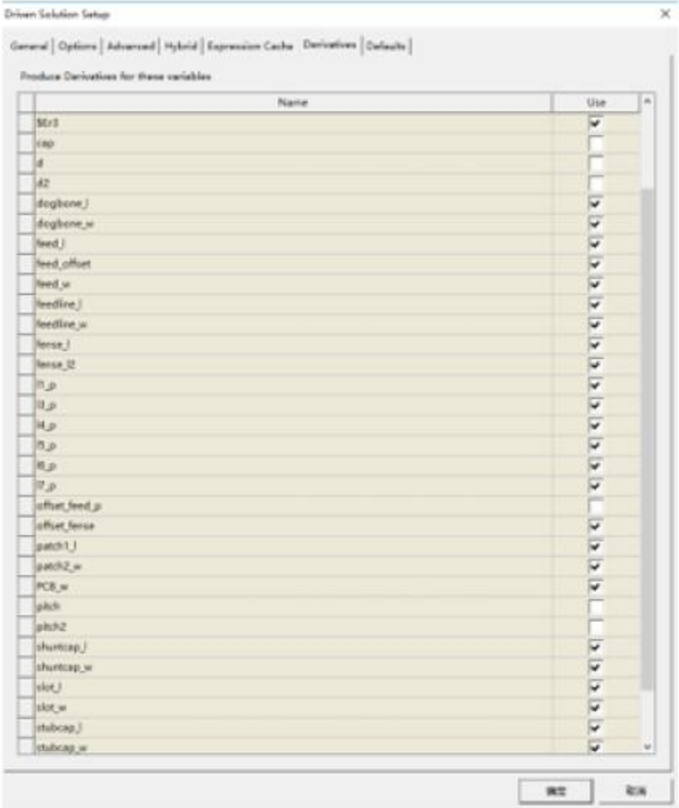
3D radiation pattern of antenna unit



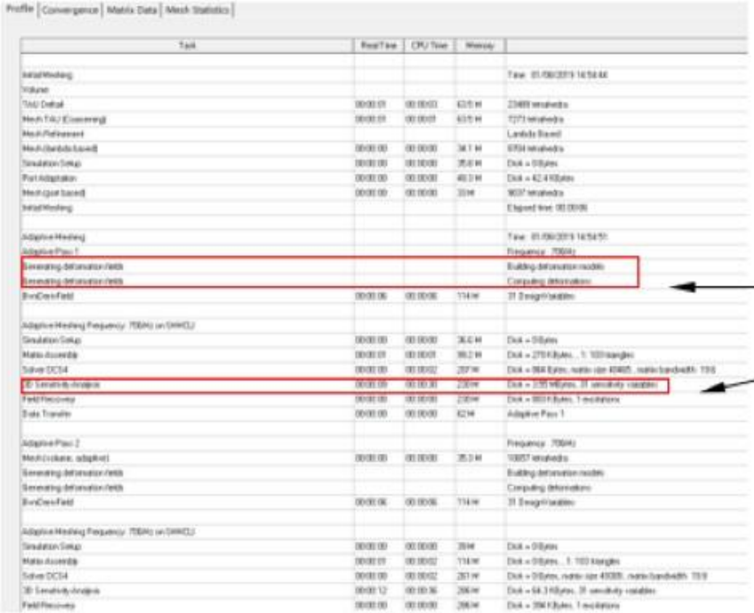
2D cut of antenna radiation pattern

- 天线工作频率V-band(57~71G),单元回损S11<-10dB
- 天线单元增益为6dB，波束宽度>90度

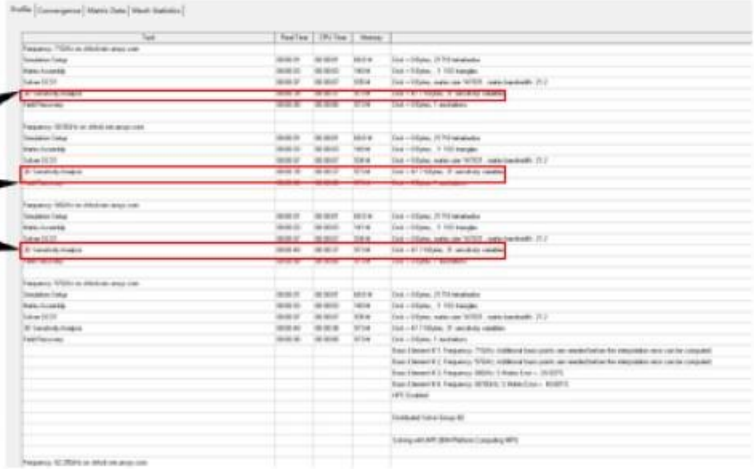
设计步骤3：伴随求导设置



设置伴随求导的参数



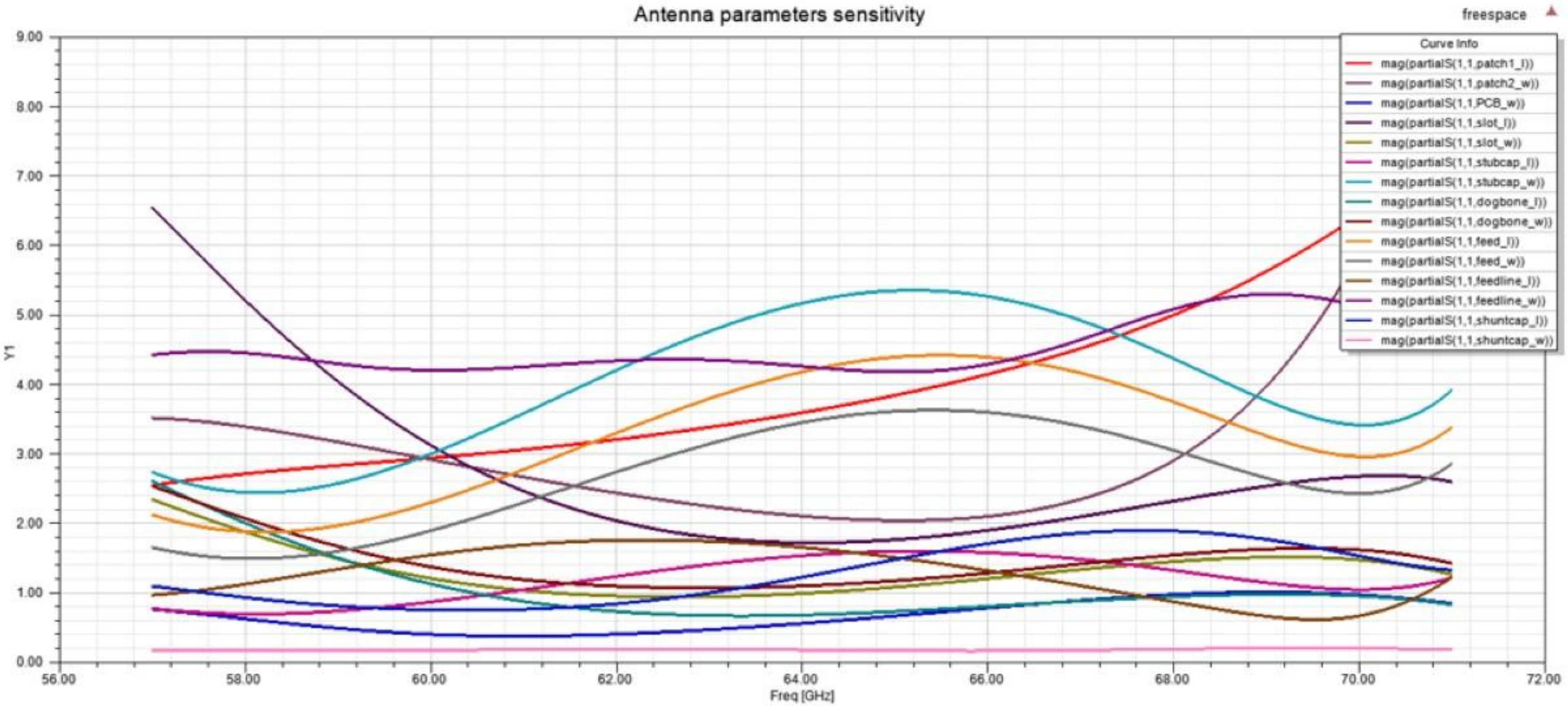
自适应迭代伴随求导过程



插值扫频伴随求导过程

仿真信息

设计步骤4: 敏感度分析

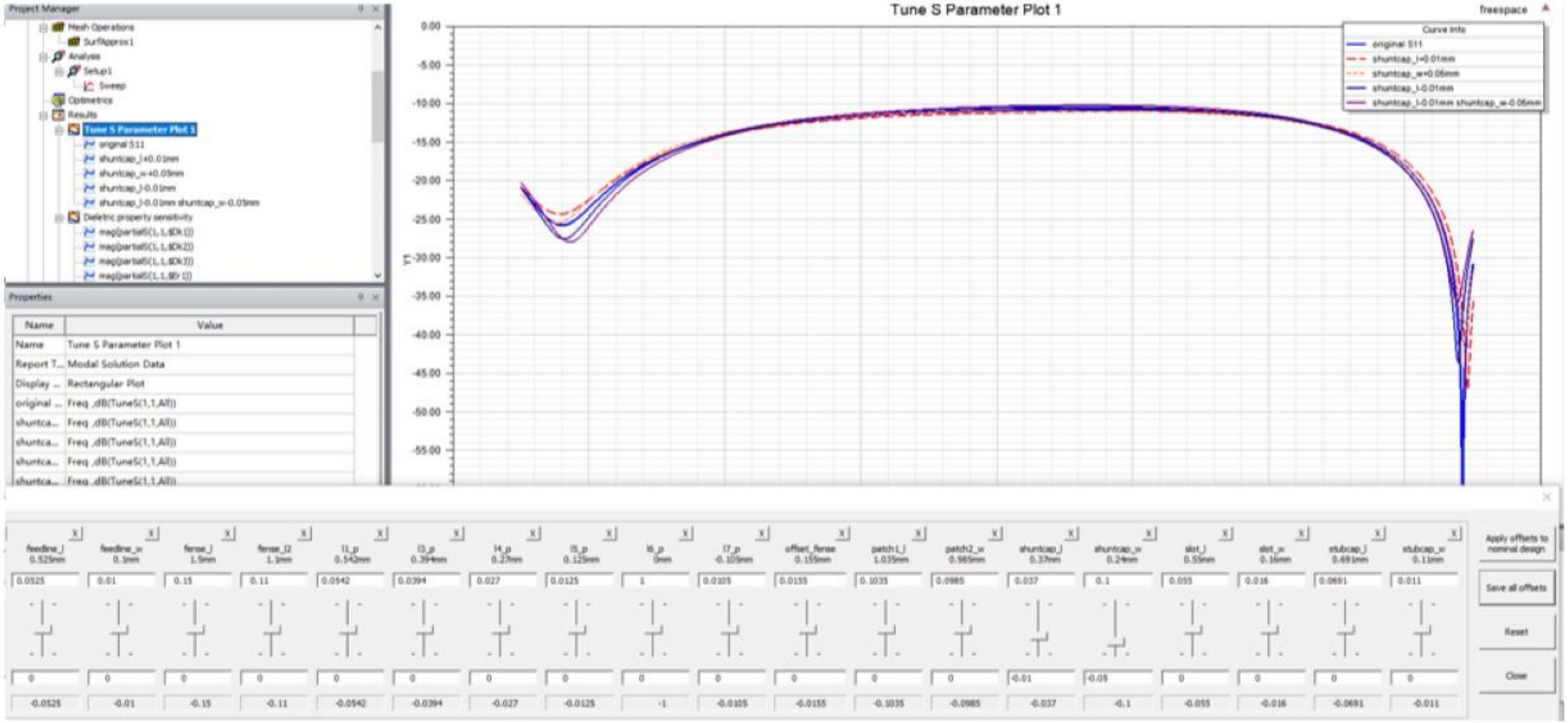


天线与馈线参数敏感度分析

伴随求导功能

- 第一步敏感度分析，一次求解得到任意多个参数，如结构参数、材料电参数的变化对S参数的影响
- 找出随频点变化的多参数中关键尺寸，越敏感的尺寸对应的曲线振幅越大，从而控制加工误差提高产品良率

设计步骤5：实时调试敏感度较高的参数以达到设计目标



馈线尺寸对于S参数影响

伴随求导功能

- 第二步实时调试，Tune Reports中调试多参数变量对S参数的影响，以达到设计预期
- Apply offsets to nominal design直接生成相关参数，为下一步参数化扫描准备

设计步骤6：参数化扫描

Setup Sweep Analysis

Sweep Definitions | Table | General | Calculations | Options

Sync #	Variable	Description
	patch1_l	Linear Step from 1.025mm to 1.045mm, step=0.01mm
	patch2_w	Linear Step from 0.975mm to 0.995mm, step=0.01mm

Add...

Edit...

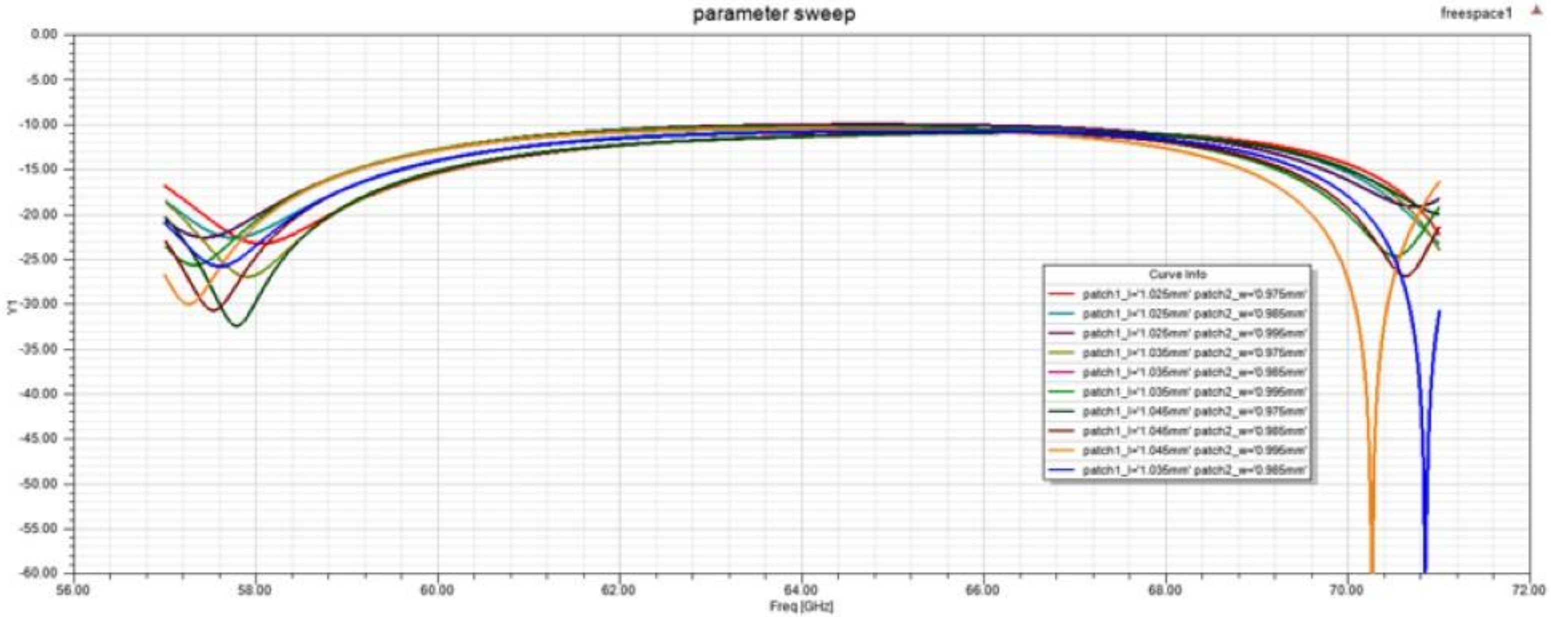
参数化扫描天线关键尺寸

Setup Sweep Analysis

Sweep Definitions | Table | General

*	patch1_l	patch2_w
1	1.025mm	0.975mm
2	1.025mm	0.985mm
3	1.025mm	0.995mm
4	1.035mm	0.975mm
5	1.035mm	0.995mm
6	1.045mm	0.975mm
7	1.045mm	0.985mm
8	1.045mm	0.995mm

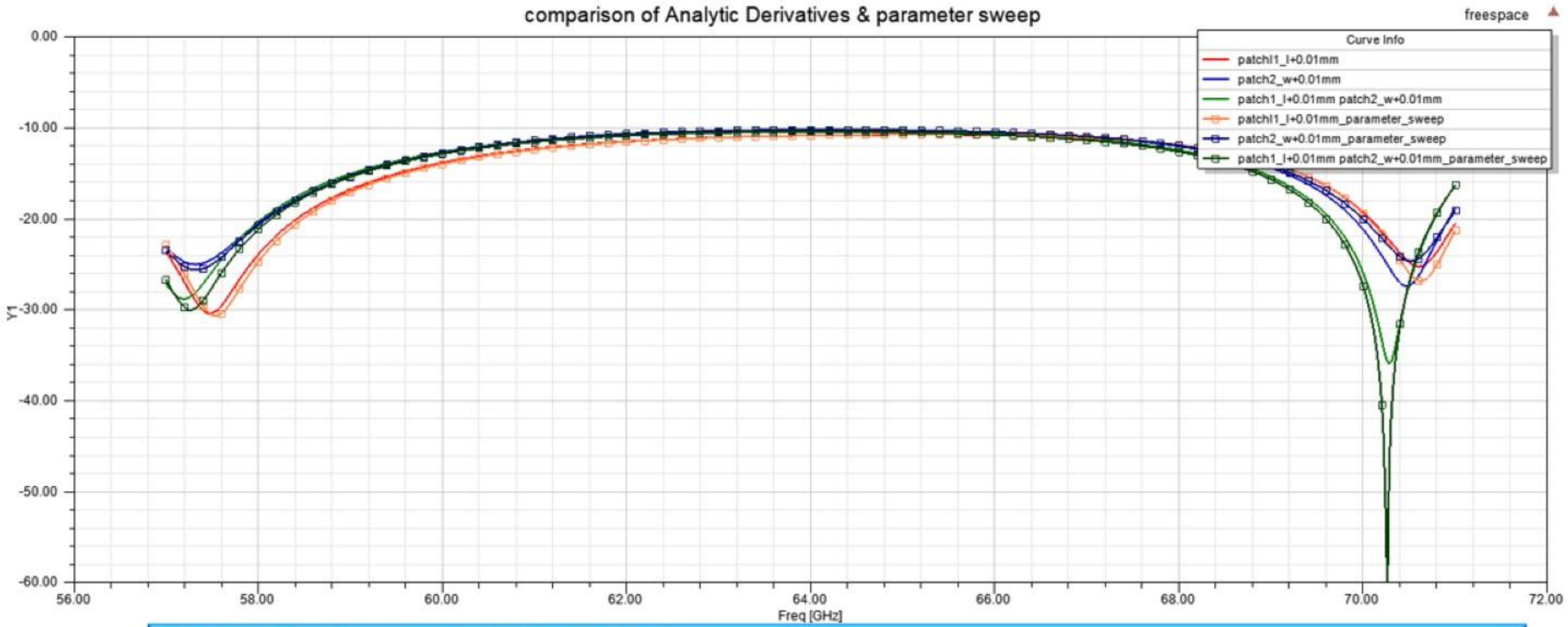
参数化扫描的排列组合



参数化扫描结果

ANSYS

设计步骤7: 参数化扫描与伴随求导结果对比



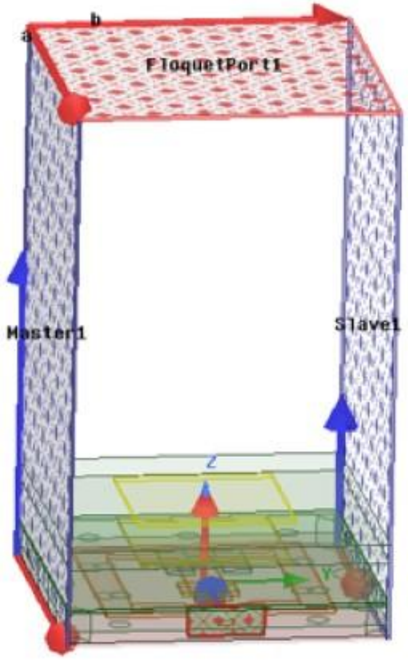
参数化扫描结果与伴随求导调试结果几乎吻合

- 伴随求导仅增加30%的求解时间，一次求解得到任意多个参数，如结构参数、材料电参数的变化对S参数的影响，求解精度高
- 仅对两三组关键尺寸进行参数化扫描，进一步确认设计的性能，仿真时间由原先的X^n 种变量组合(X为可变情况，n为变量个数)缩减为仅有$X^{2\sim3}$种组合，极大程度上缩减仿真时间

ANSYS

2.阵列扫描盲区验证

Floquet模式分析



Mode	Polarization State	m	n	Attenuation (db/length)
1	TE	0	0	0.00
2	TM	0	0	0.00
3	TE	-1	0	10.82
4	TE	0	-1	10.82
5	TM	-1	0	10.82
6	TM	0	-1	10.82
7	TE	1	0	23.23
8	TE	0	1	23.23

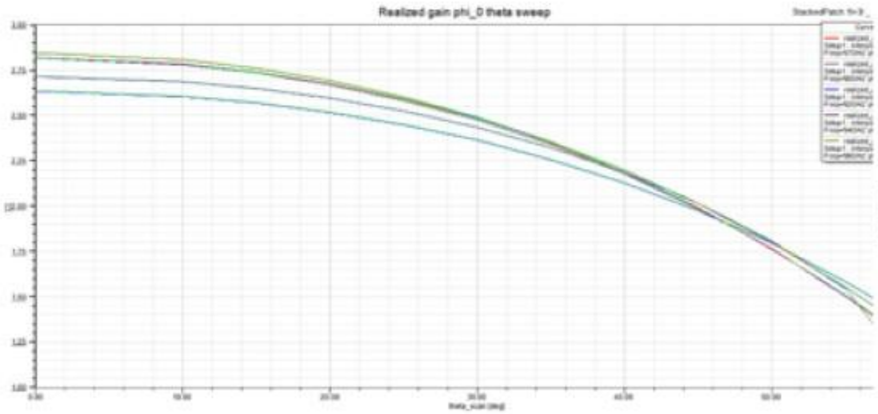
Floquet模式计算器可以仿真主模和高次模式下的场分布，同时通过单位长度衰减掉其他不关注模式，这取决于以下三方面

- 栅格大小
- 求解频率
- 扫描角

扫描盲角分析

Realized Gain calculated directly from Floquet Transmission Coefficients

$$G = \frac{4\pi A}{\lambda^2}\left(\left|TM_{0,0}\right|^2 + \left|TE_{0,0}\right|^2\right)\cos(\theta_s)$$



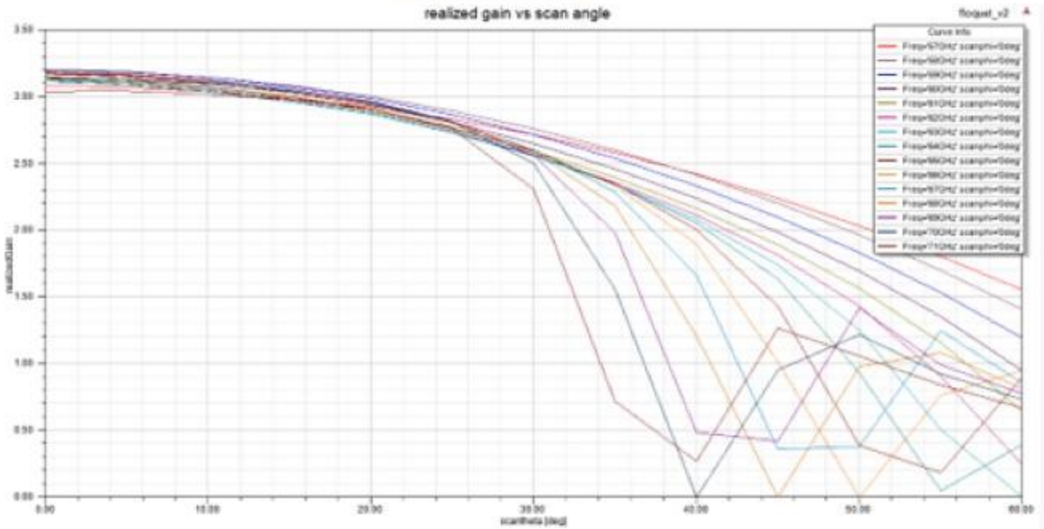
Realized gain at Phi=0 frequency sweep

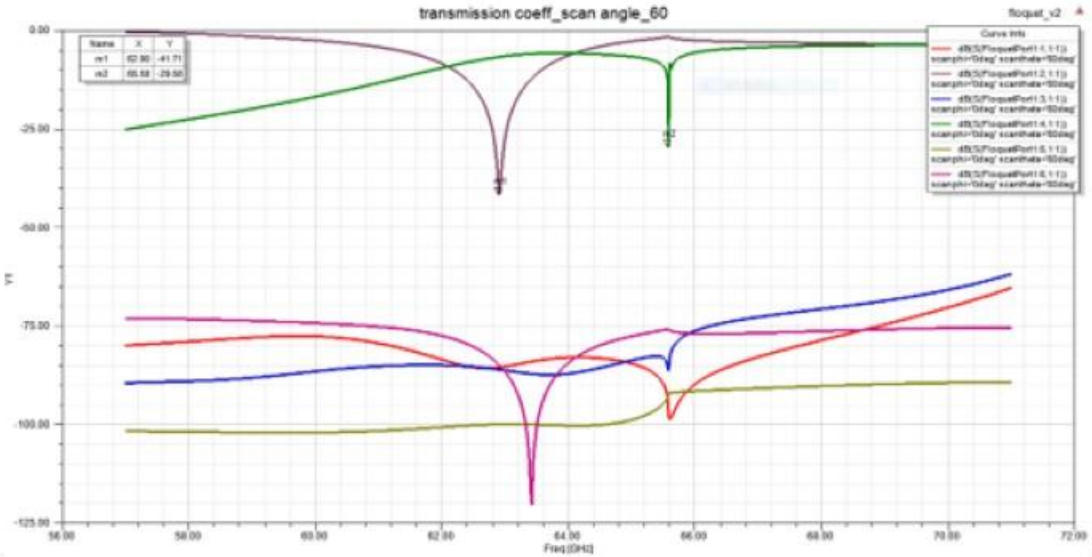
Realized gain at Phi=90 frequency sweep

- **From Floquet mode simulation, the realized gain doesn't degraded when beam scan from theta 0~60 degree, it indicates no scan blindness were found between 56~71GHz**
- **It found the realized gain drops when beam scan from theta from 50~60 deg, it indicates there is scan blindness at phi=90 (E-plane)**

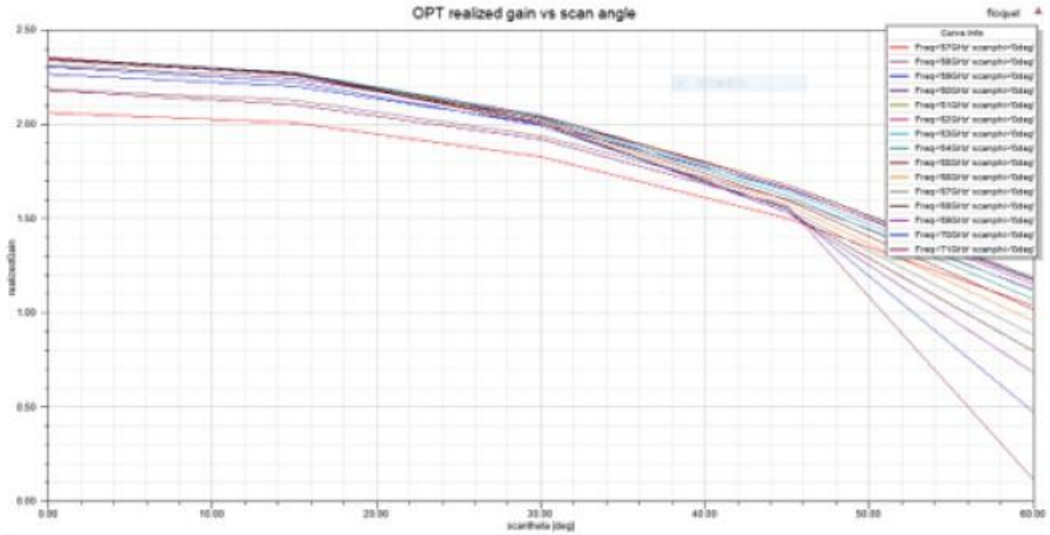
天线单元优化

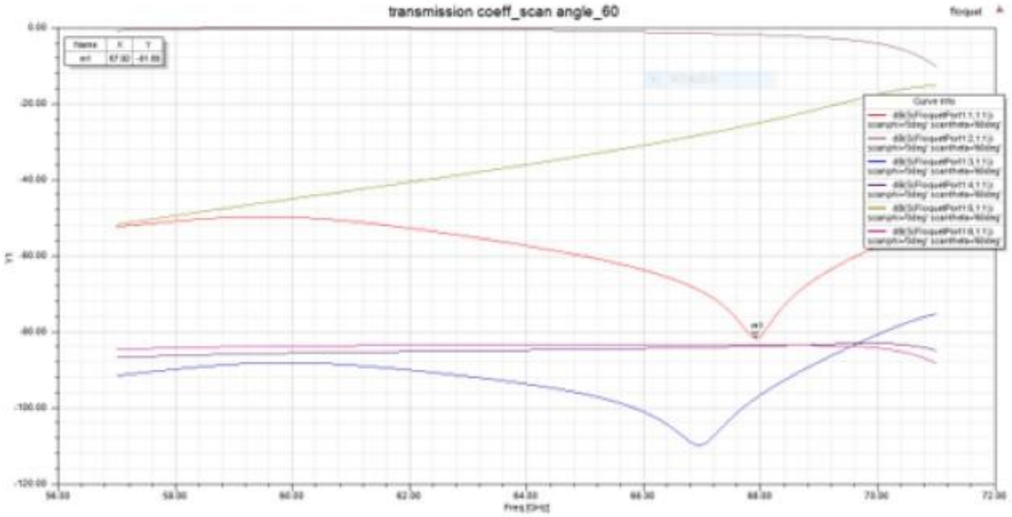
优化前



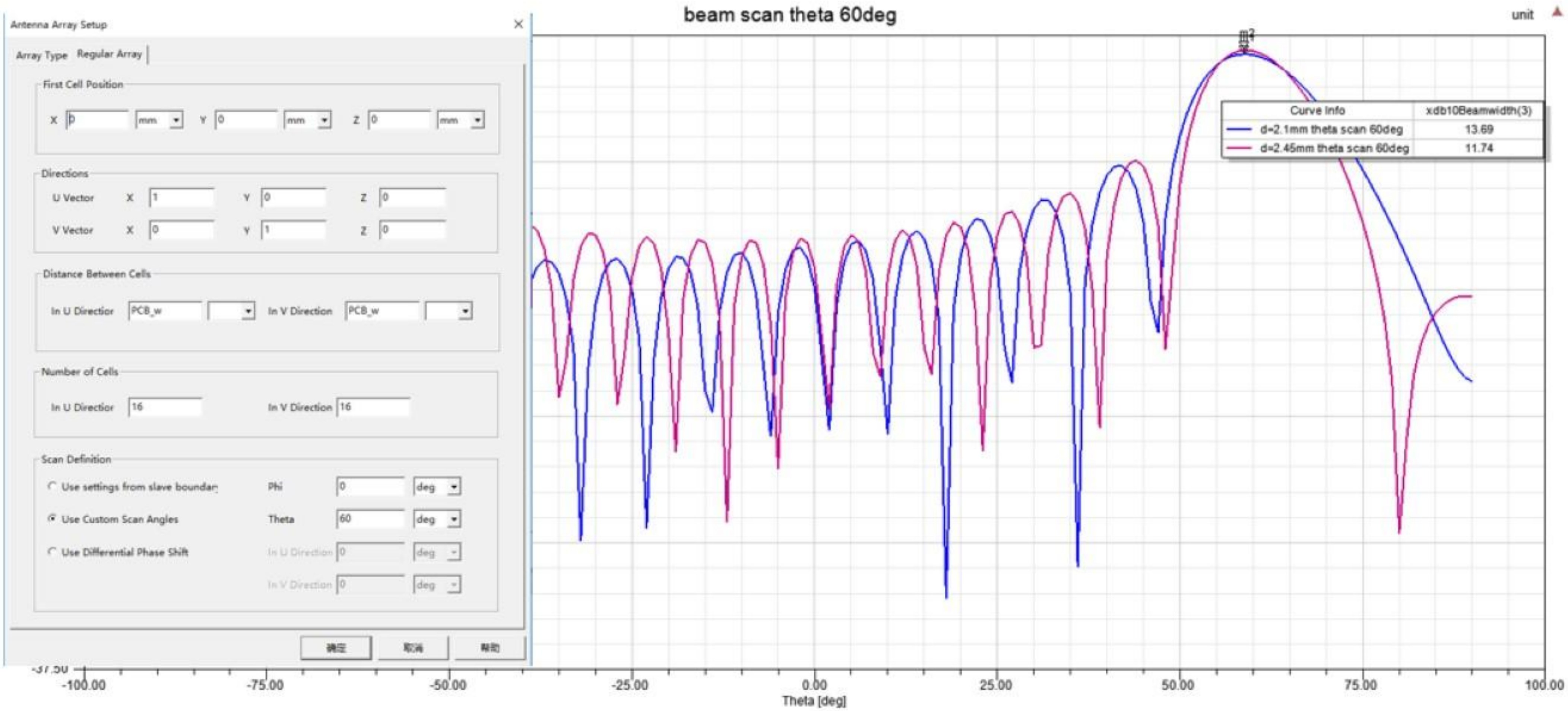


优化后



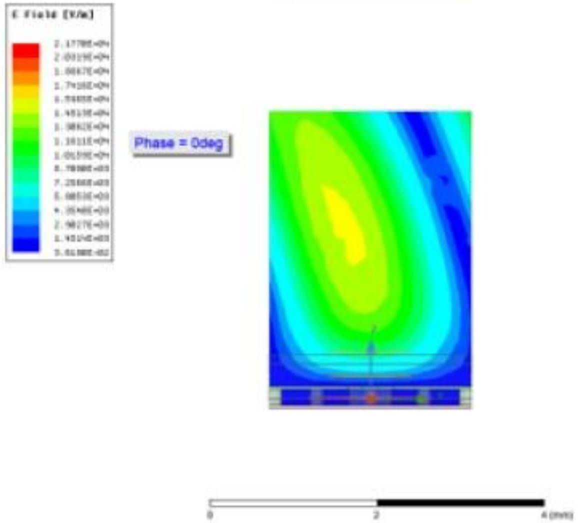


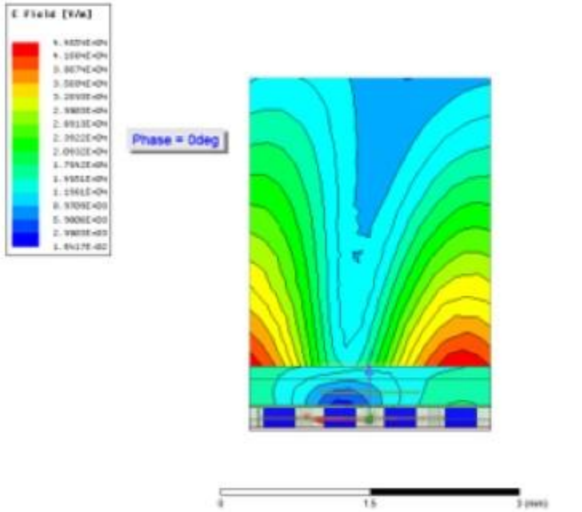
阵因子—Array factor



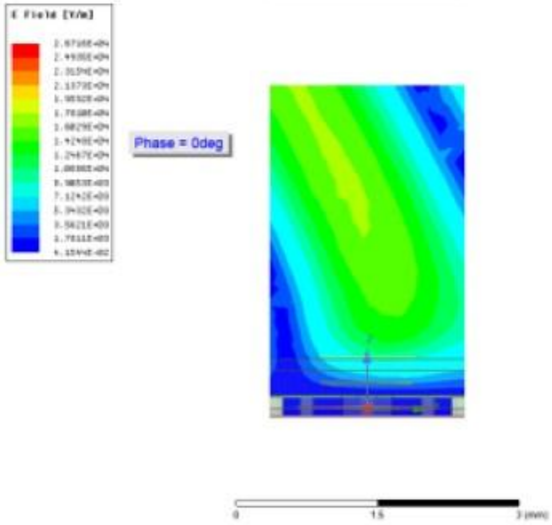
天线单元优化前后切向电场对比

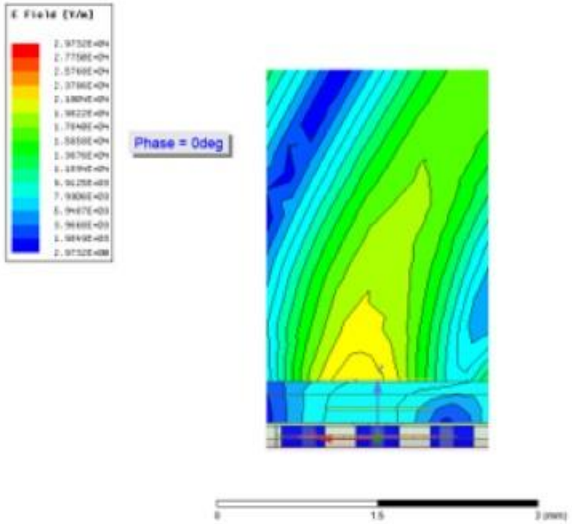
优化前





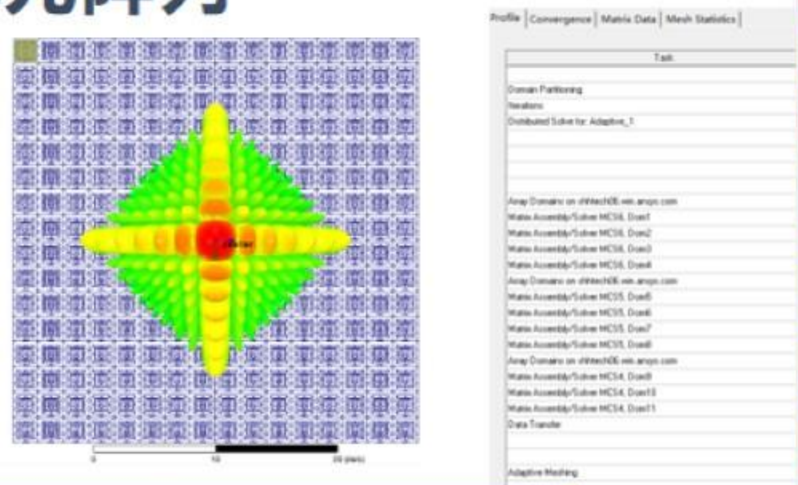
优化后



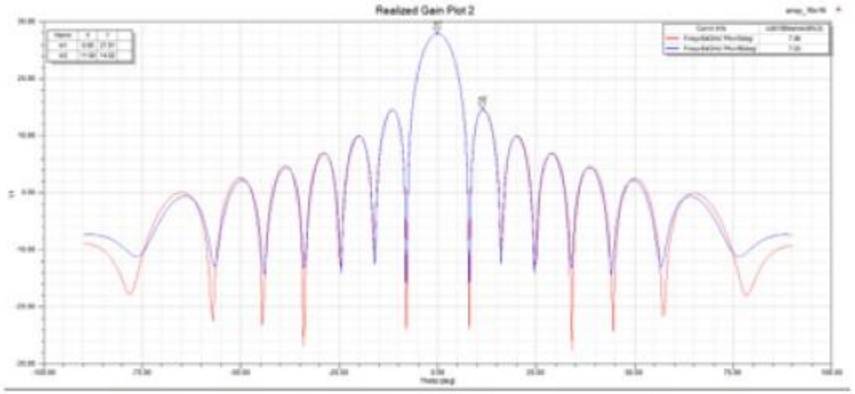


3.有限大阵仿真

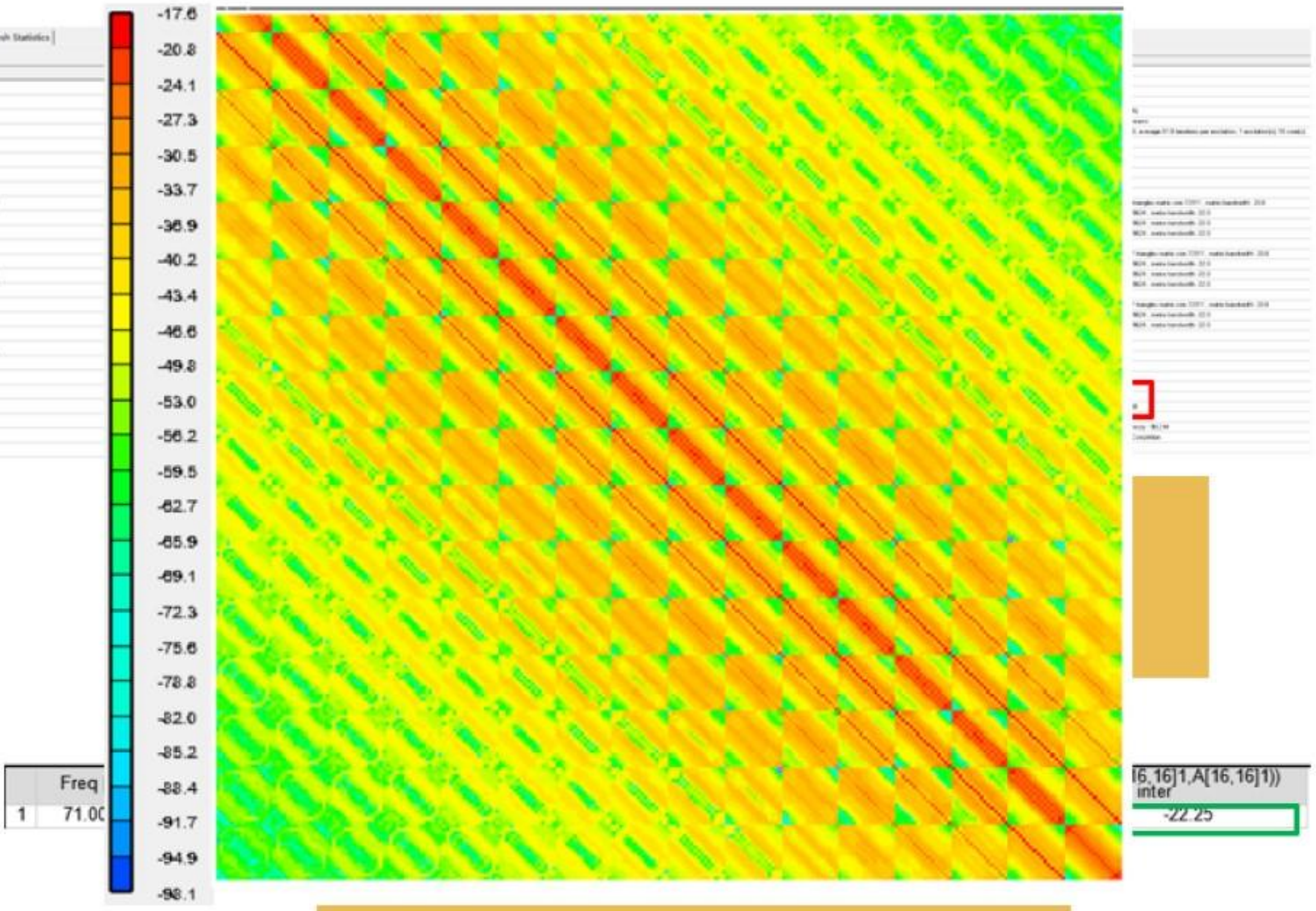
256天线单元阵列



antenna array simulation using FA-DDM



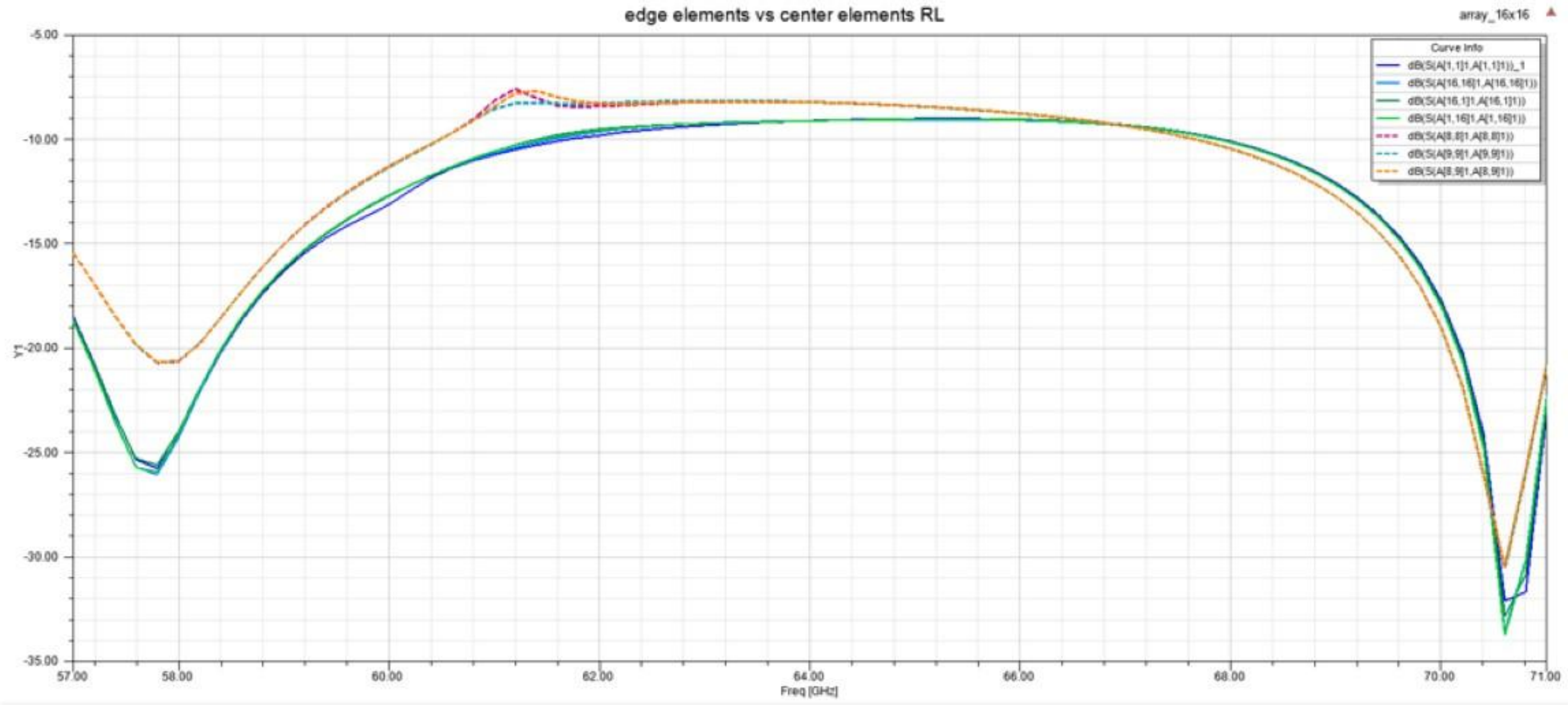
Array 2D radiation pattern at 64 GHz



Antenna elements coupling/isolation level

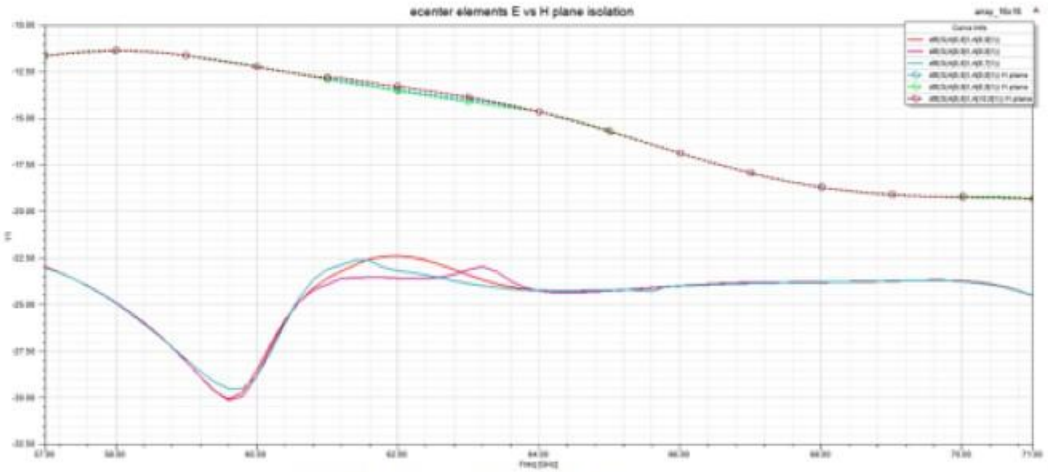
- Rectangular array with 16X16 elements, when array feed uniformly, peak gain is 27.8dB, HPBW is 7.0 deg
- When array feed uniformly, the active S parameter of center element is < -20 dB, the edge elements is < -22 dB

边缘单元 vs 中心单元回损

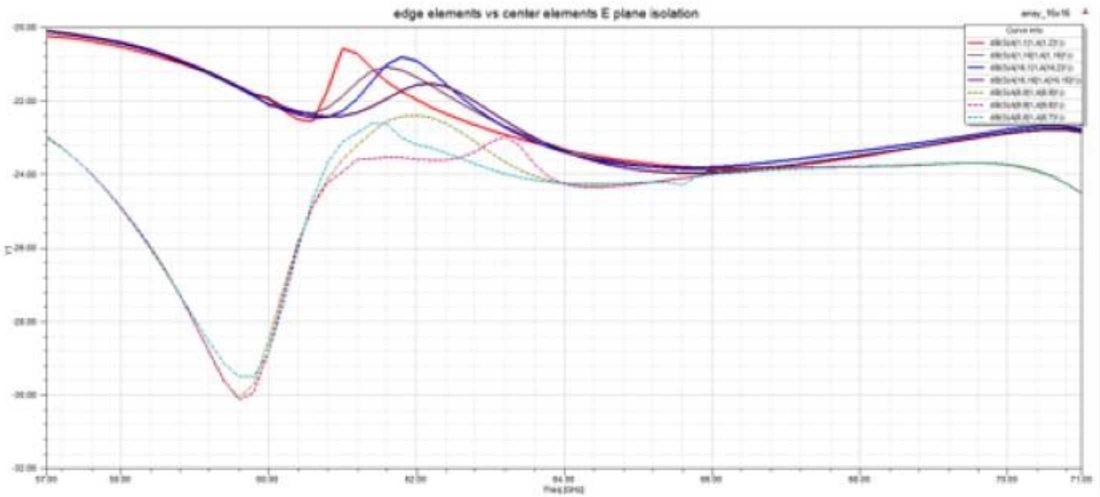


- In general, return loss for center element < -8dB within band when broadside beam
- Return loss for edge element < -10dB within band

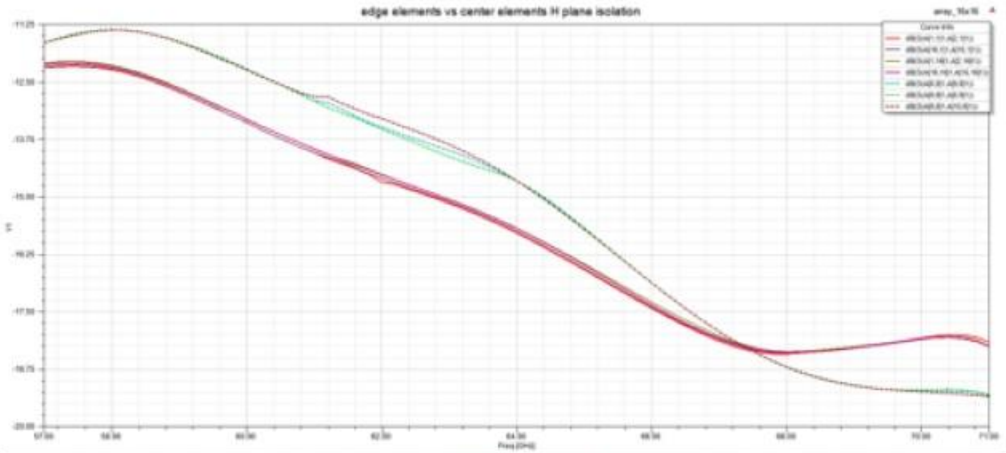
边缘单元 vs 中心单元隔离度



中心单元E、H面隔离度



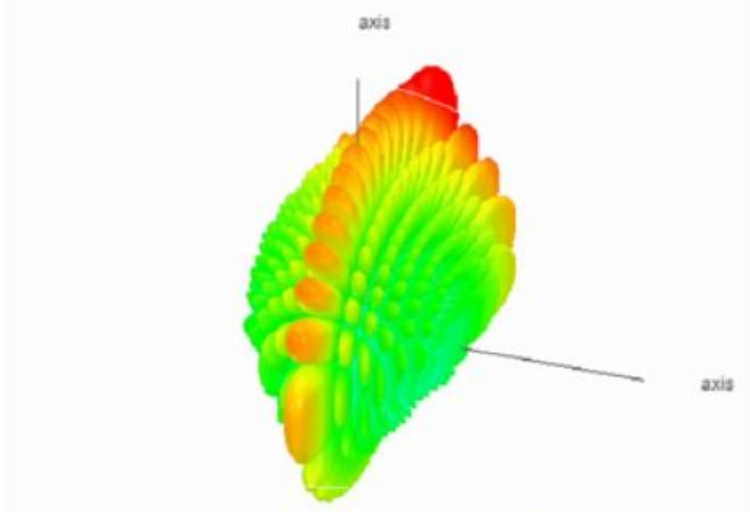
边缘单元 vs 中心单元E面隔离度



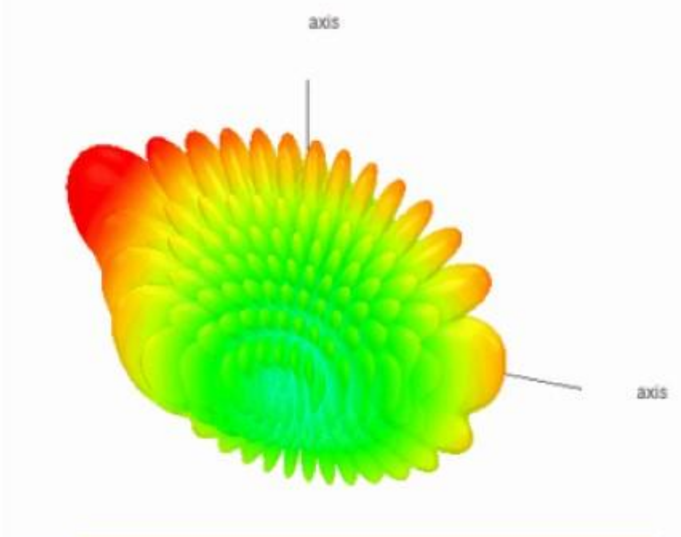
中心单元 vs 边缘单元H面隔离度

- In general, isolation between adjacent element in E plane is 10.5 dB better than H plane
- Isolation for center element in E plane is dB better than edge elements in E plane
- Isolation for center element in H plane is almost same as edge elements in H plane.

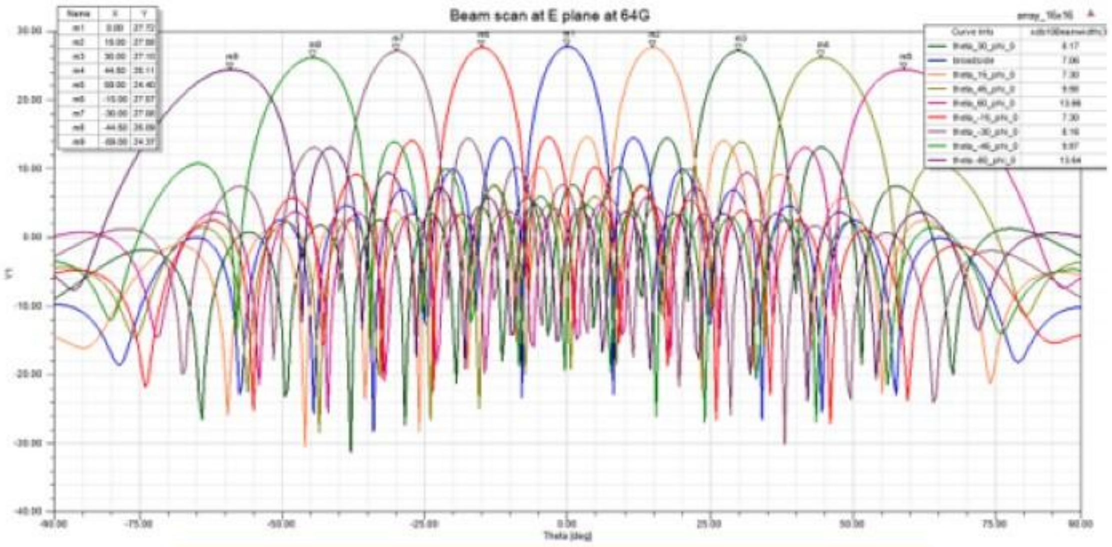
沿E / H面波束扫描



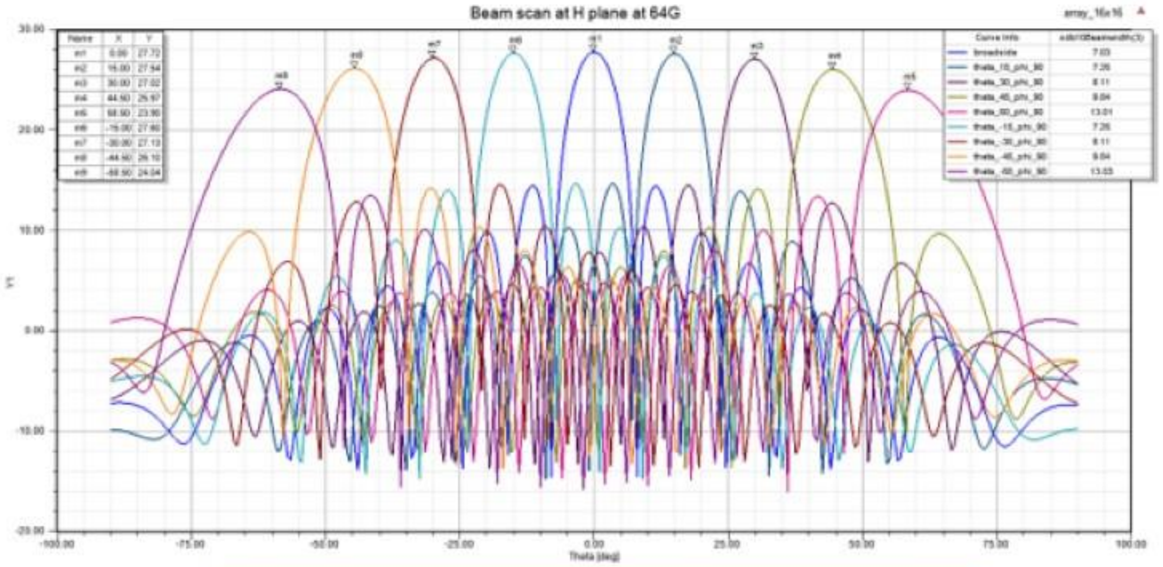
3D beam scan animation for E plane



3D beam scan animation for H plane



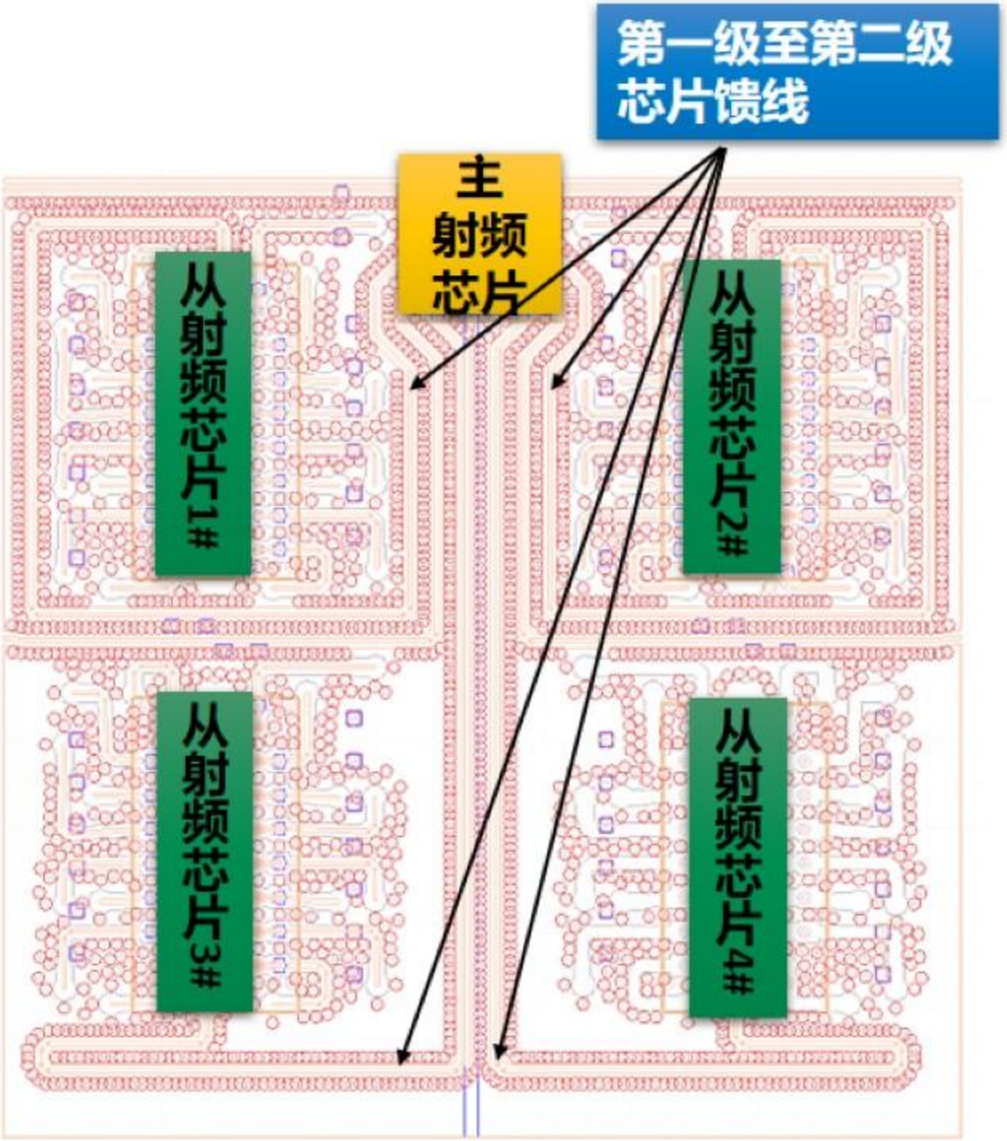
2D radiation pattern for beam scan at E plane



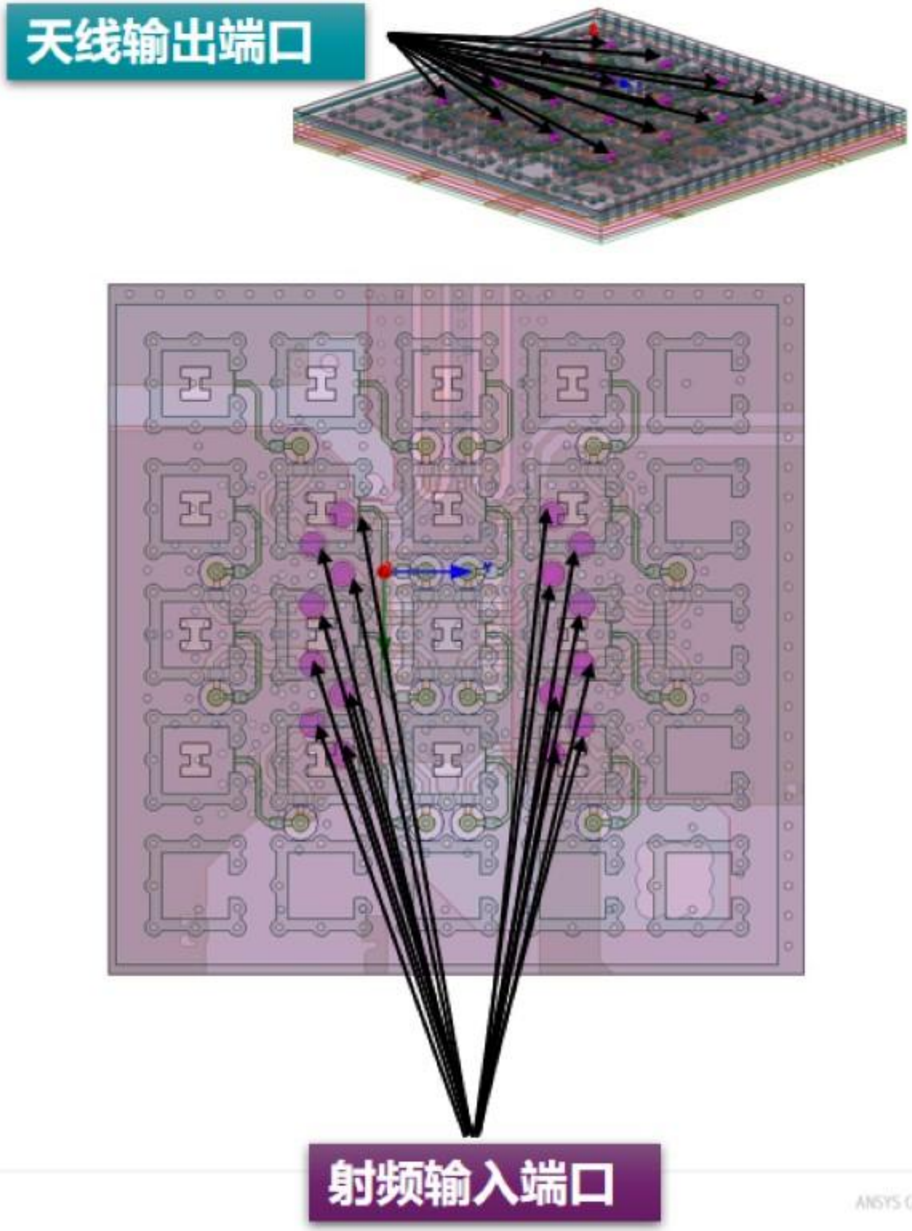
2D radiation pattern for beam scan at H plane

4.复杂馈线仿真

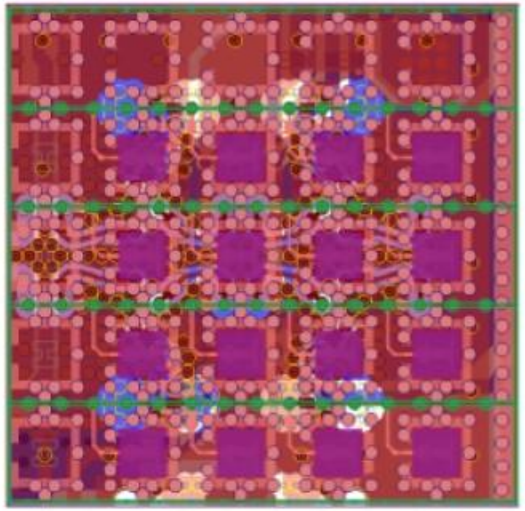
复杂馈线仿真(第一级芯片)



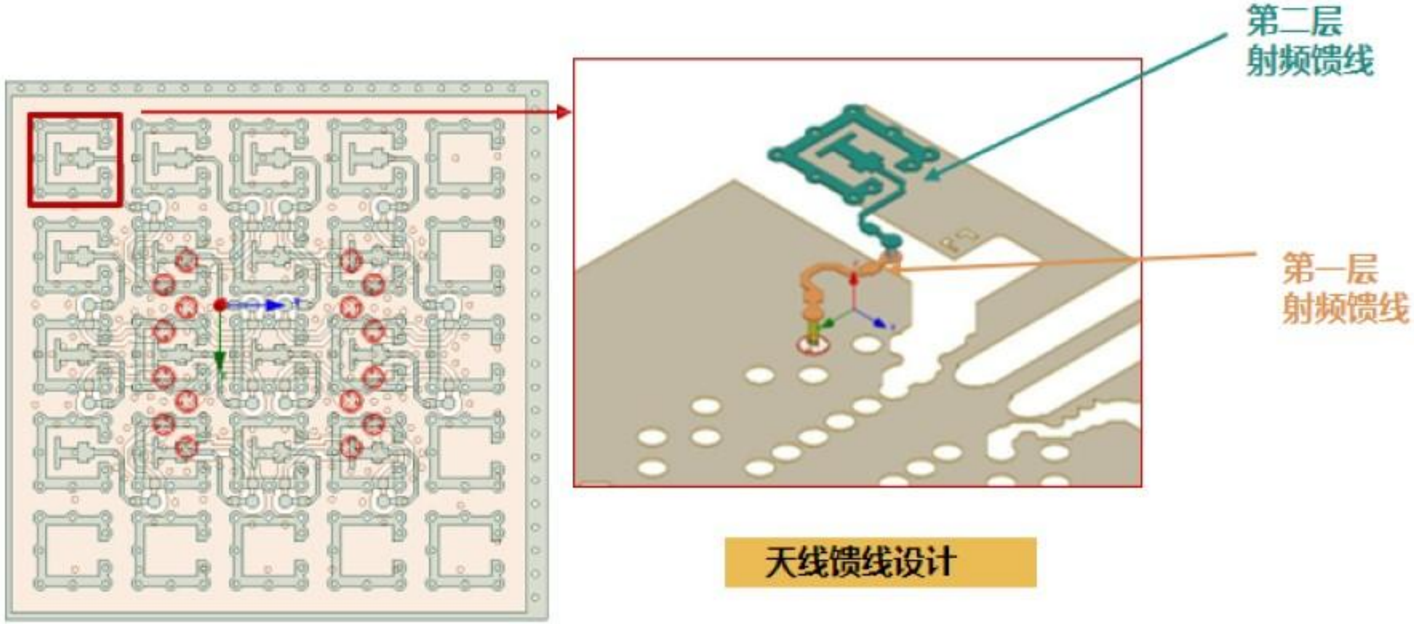
复杂馈线仿真(第二级子射频芯片至天线)



子射频芯片的布局



Top view

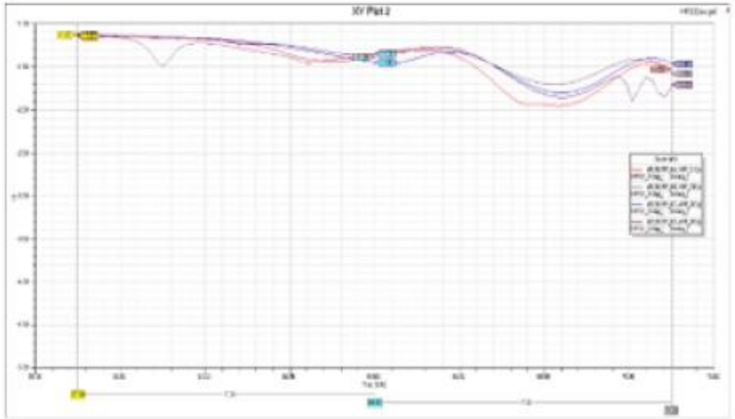


天线馈线设计

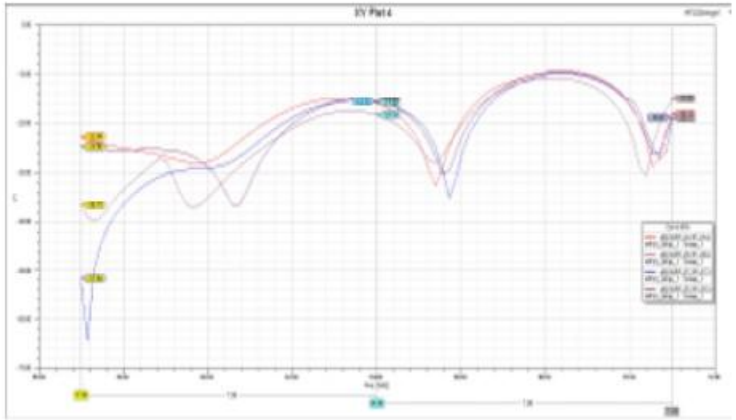
bottom view

Side view

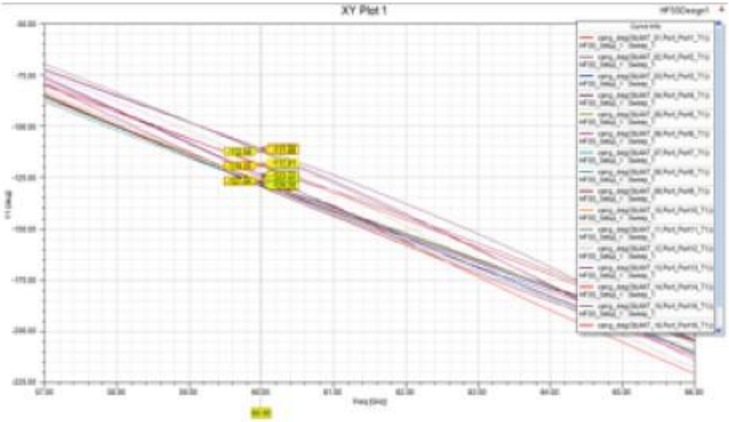
复杂馈线仿真结果



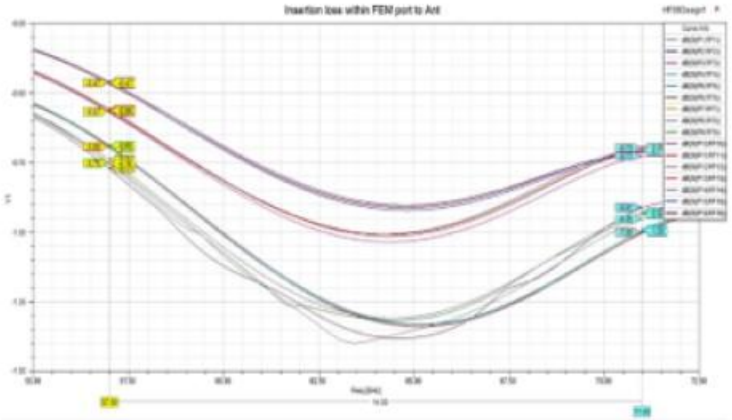
第一级主芯片至子芯片插损



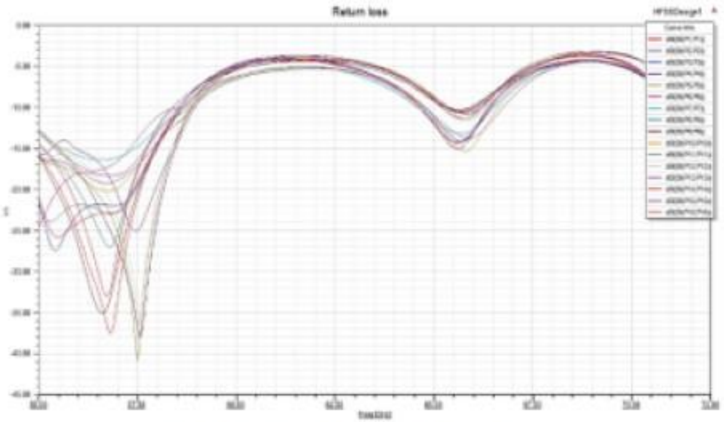
第一级主芯片至子芯片回损



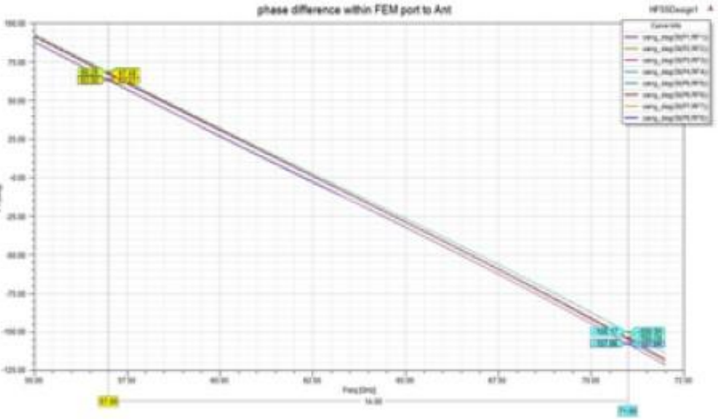
第一级主芯片至子芯片相位延迟



第二级子芯片至天线口插损



第二级子芯片至天线口回损

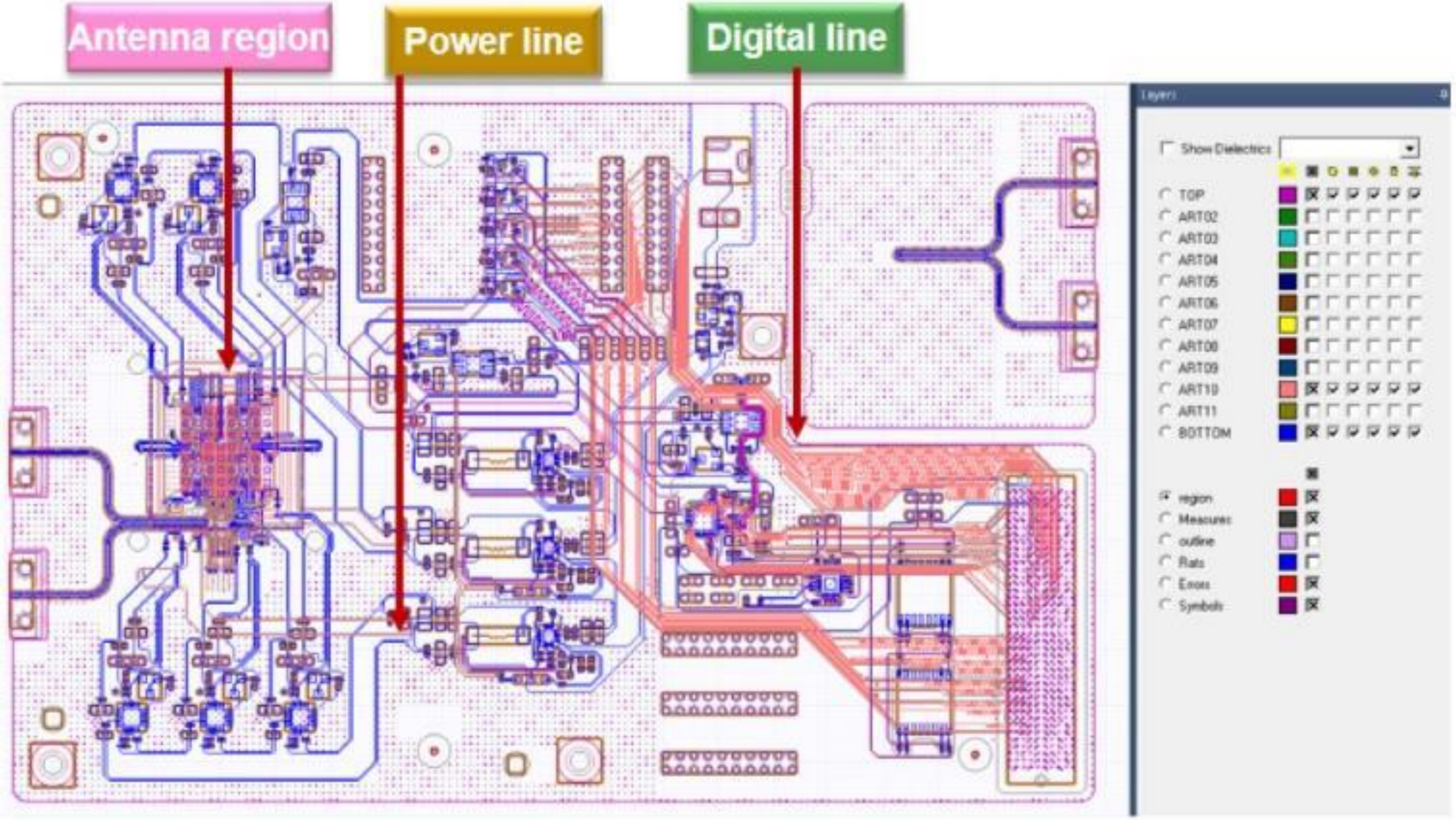


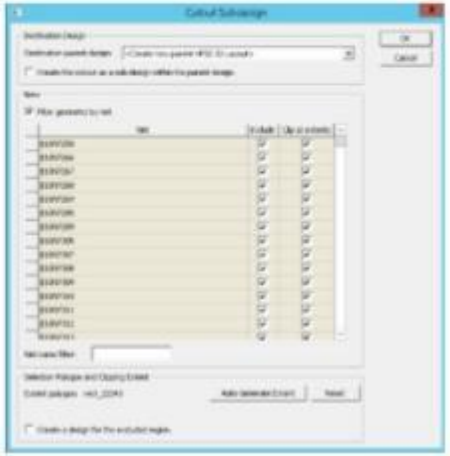
第二级子芯片至天线口相位延迟

5.射频芯片与封装天线一体化设计

Step 1:导入EDA文件

- 此PCB为高速高频板，共12层叠层结构，含5颗RFIC芯片，PCB含天线、馈线、电源、数字走线结构

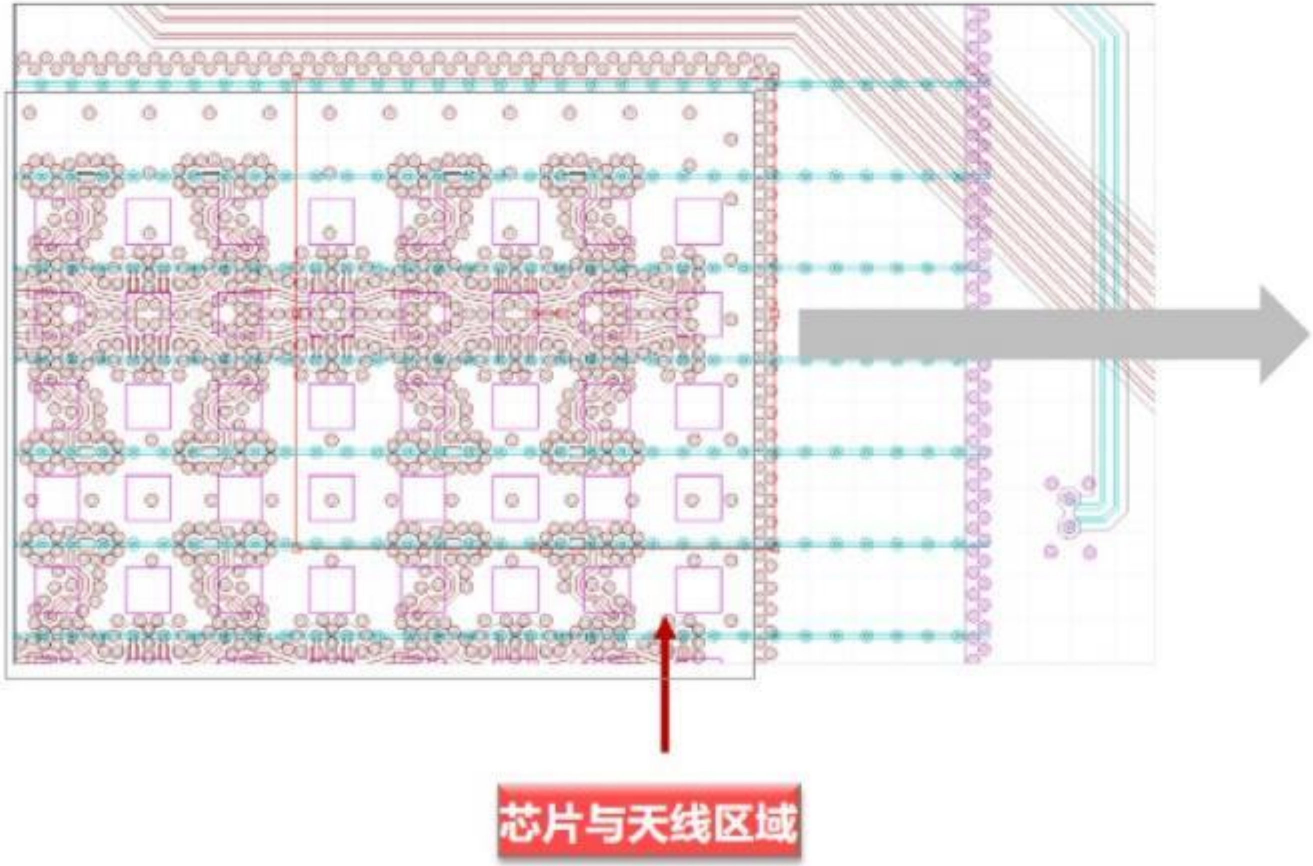


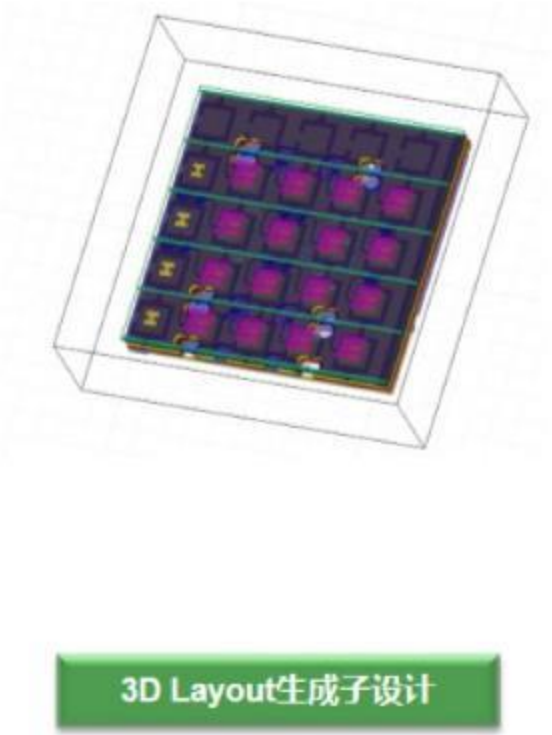


提取与导入对话框中显示出所有的网络节点Nets，勾选所需导入的节点，及是否需要自动建立端口，此案例为默认导入所有节点

Step 2:截取天线区域

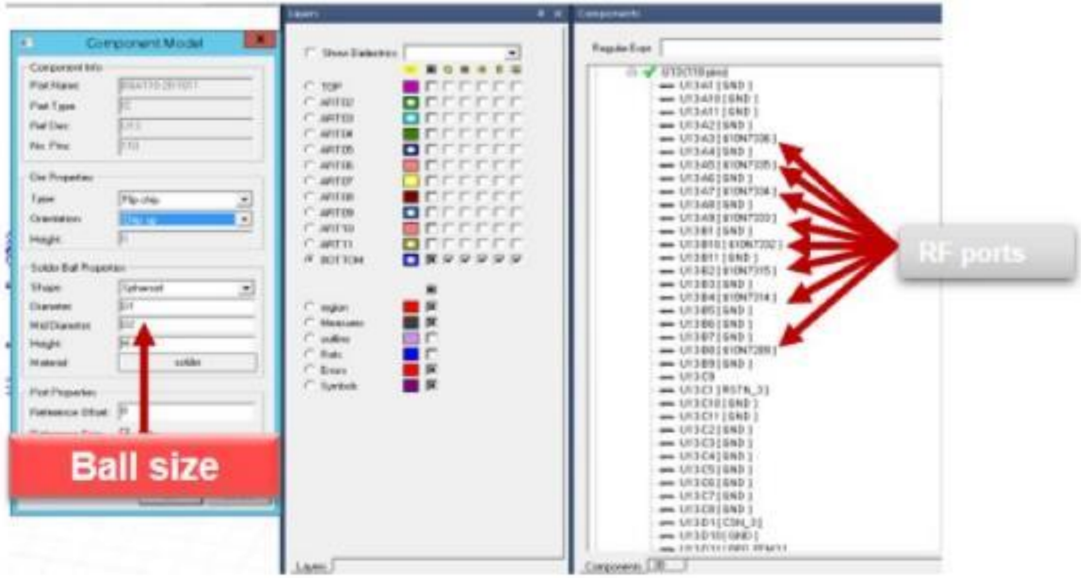
- 选择合适的天线区域，框选单FEM画出region
  - 注意选择合适的天线单元和馈线区域，region可以稍大于单FEM尺寸
  - 截取生成的子设计需一定的简化，除去不影响电性能的过孔与走线，减少仿真时间

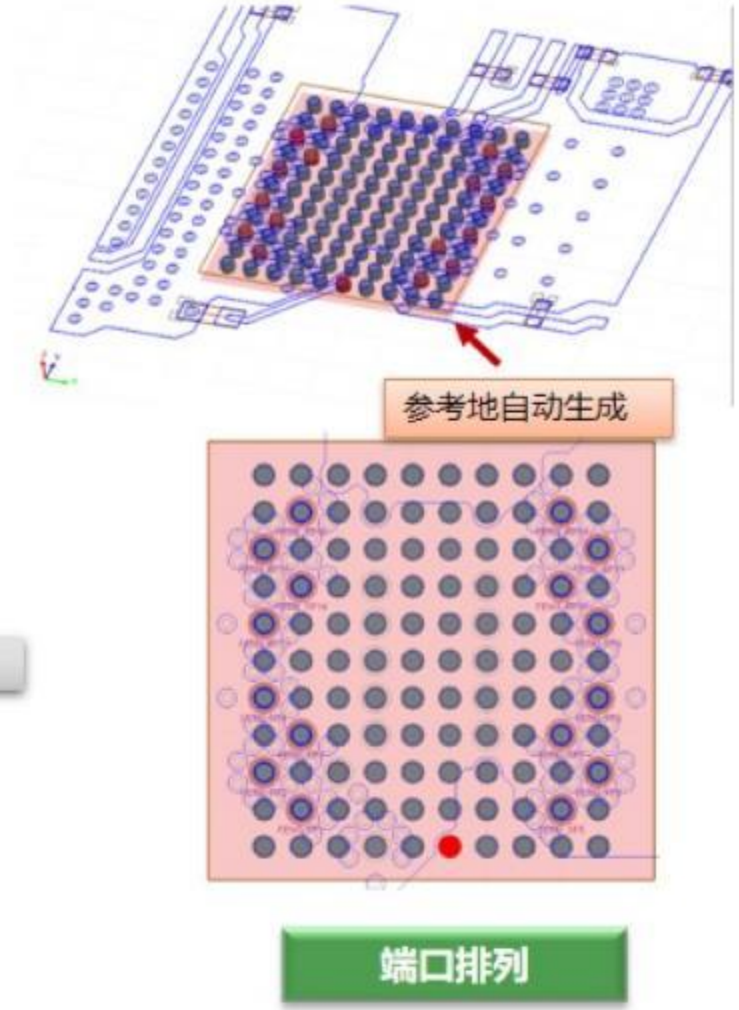




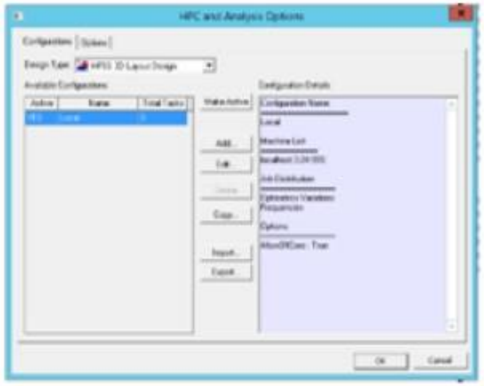
Step 3:建立端口

- 选择FEM中的射频通道建立相应的端口
  - 芯片封装类型：Flip chip
    - ➢ 方向：chip up
  - 焊球类型：Spheroid 球形体
    - ➢ 上直径：0.3mm
    - ➢ 中心直径：0.32mm
    - ➢ 高度：0.22mm





Step 4:求解设置



求解设置

扫频设置

HPC设置

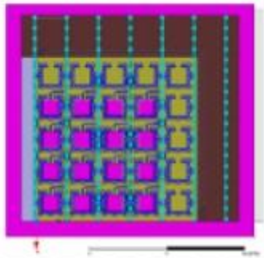
精度对比

模型

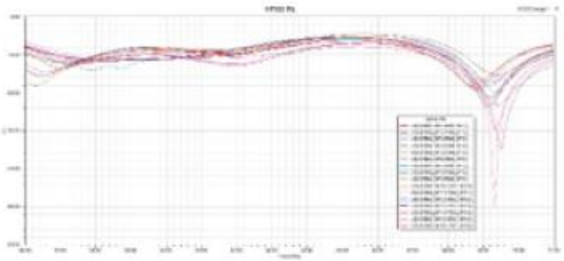
仿真时间

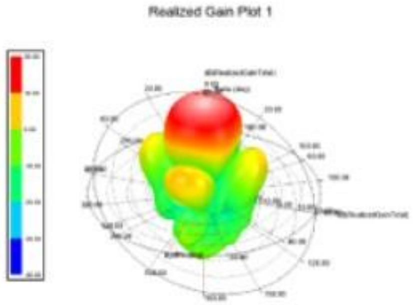
仿真精度

HFSS 3D

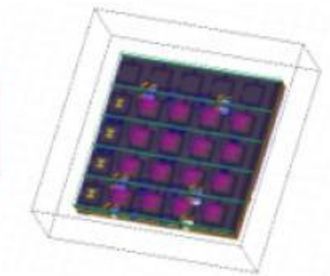


Adaptive Pass 10				Frequency: 64GHz
Mesh (volume, adaptive)	00:20:33	00:20:30	2.9 G	2793943 tetrahedra
Adaptive Meshing Frequency 64GH...				
Simulation Setup	00:09:14	00:09:14	3.81 G	Disk = 0 KBytes
Matrix Assembly	00:18:43	00:35:52	63.2 G	Disk = 0 KBytes, 2200609 tetrahedra, 16 lumped port(s)
Solver DCS48	00:53:39	07:51:28	129 G	Disk = 0 KBytes, matrix size 15327555, matrix bandwidth 21.2
Field Recovery	00:06:09	03:09:35	129 G	Disk = 64061 KBytes, 16 excitations, Average Order 0.999962
				Adaptive Passes converged
Adaptive Process				Elapsed time 11:36:54 Hfss ComEngine Memory: 4.5 G
Total	10:46:12	62:56:41		Time: 12/21/2017 04:25:47, Status: Normal Completion



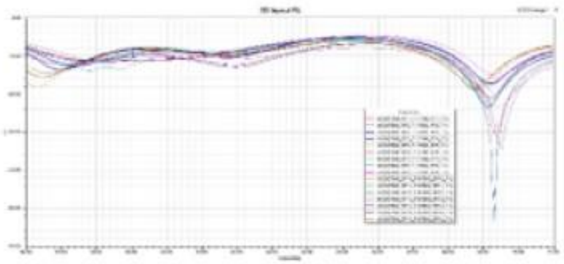


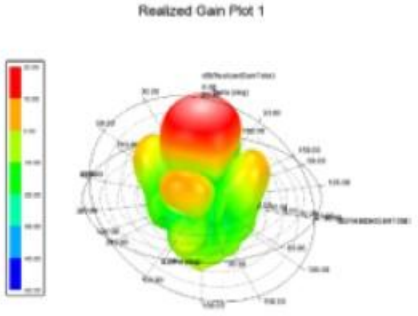
3D Layout



Adaptive Meshing Fr...				
Simulation Setup	00:07:35	00:07:35	3.07 G	Disk = 0 KBytes
Matrix Assembly	00:15:08	00:50:01	50.3 G	Disk = 10 KBytes, 1786750 tetrahedra, 16 lumped port(s)
Solver DCS48	00:35:34	05:26:39	92.8 G	Disk = 0 KBytes, matrix size 12154430, matrix bandwidth 21.1
Field Recovery	00:04:53	02:50:17	92.8 G	Disk = 59369 KBytes, 16 excitations, Average Order 0.999964
				Adaptive Passes converged
Adaptive Process				Elapsed time 07:01:36 Hfss ComEngine Memory: 4.32 G
Total	06:42:21	47:31:16		Time: 12/21/2017 23:22:42, Status: Normal Completion

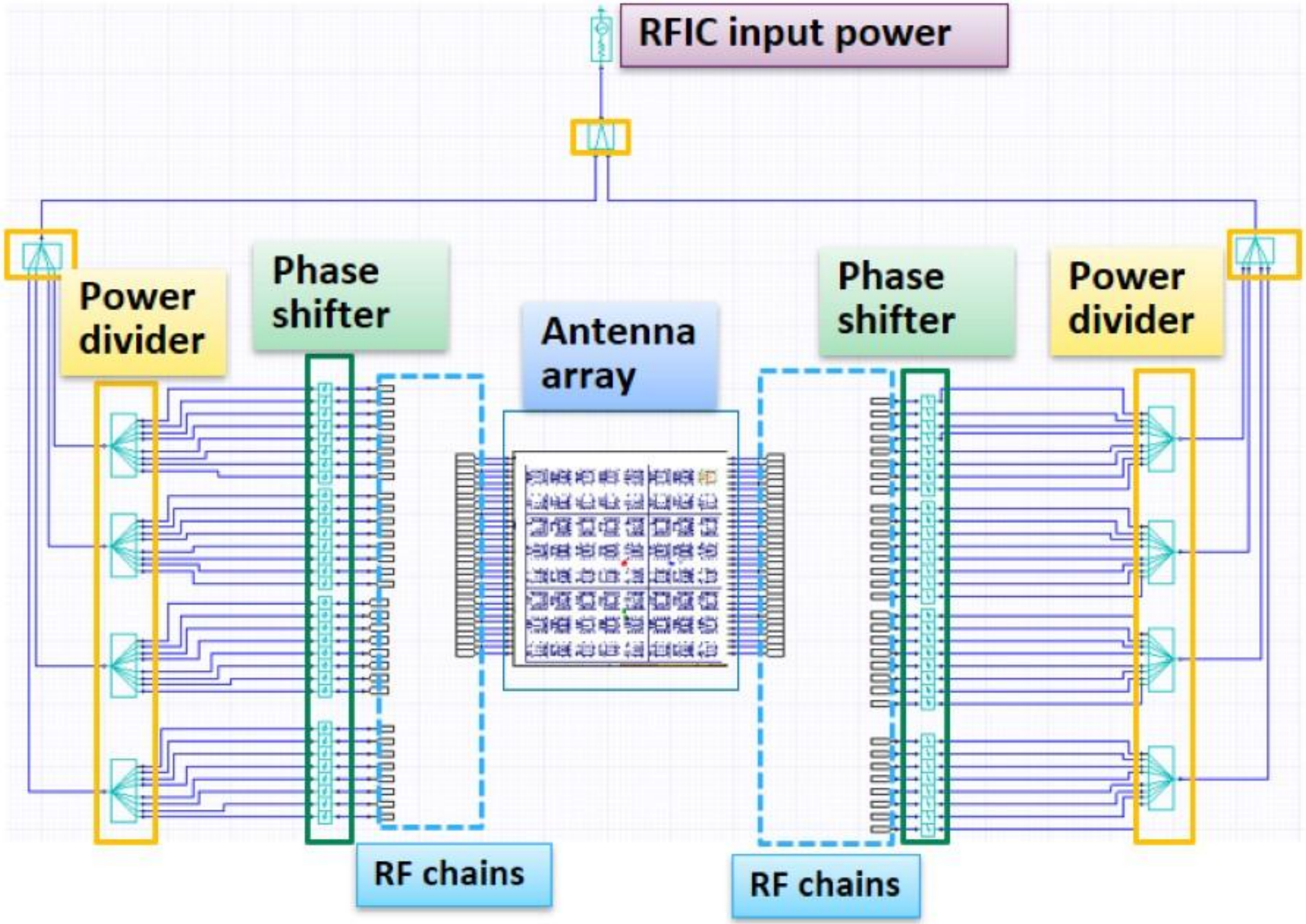
Speed up 2x



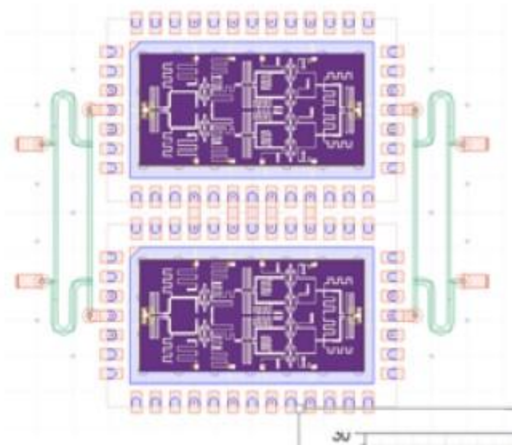


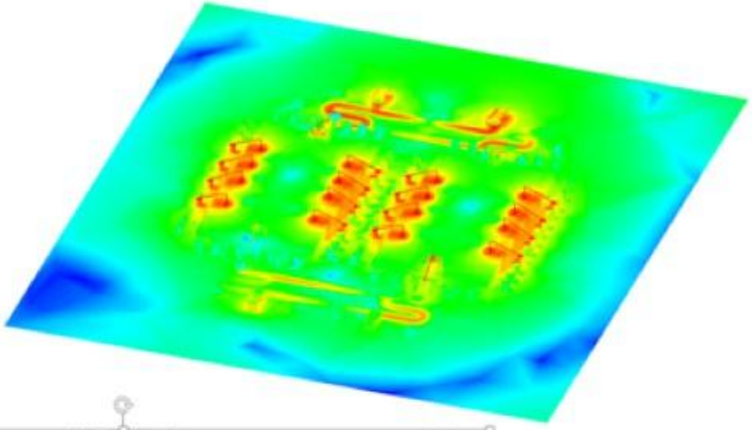
6.芯片有源器件电热分析

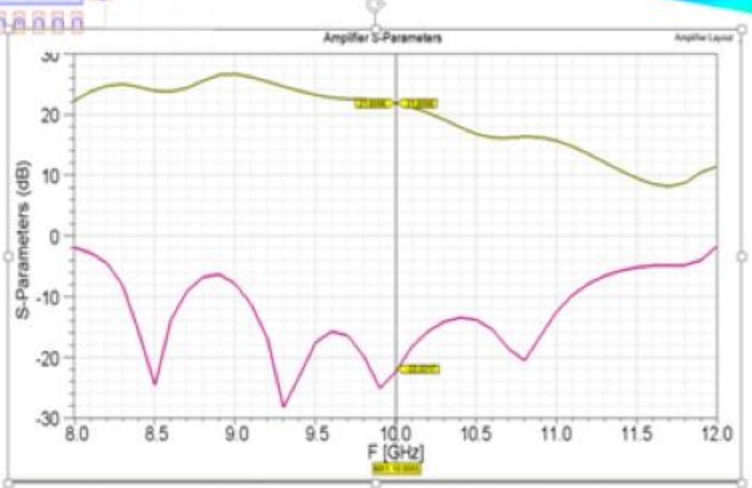
含射频芯片天线系统链路仿真



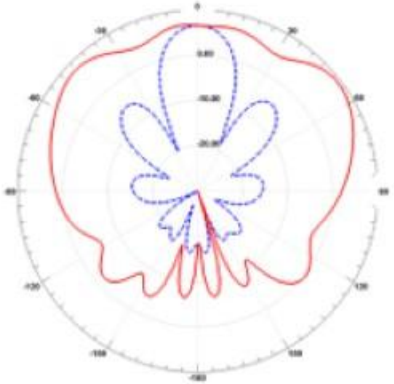
芯片封装系统仿真—CPS



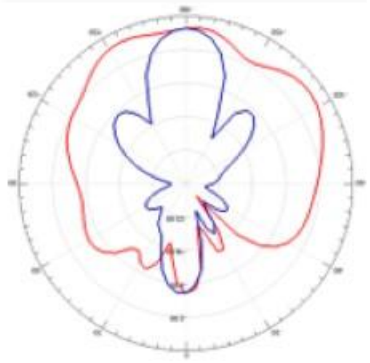




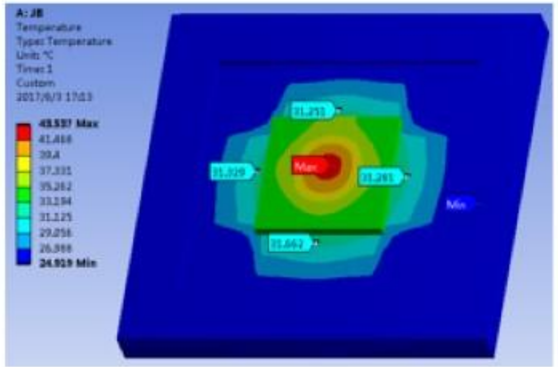
天线单独仿真

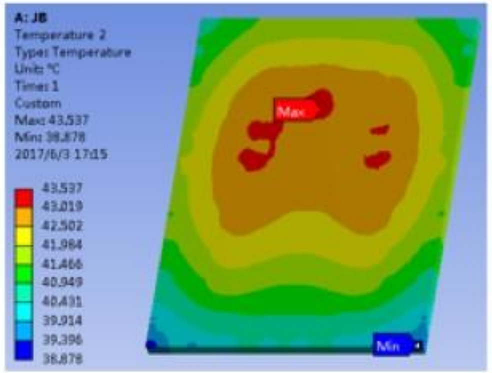


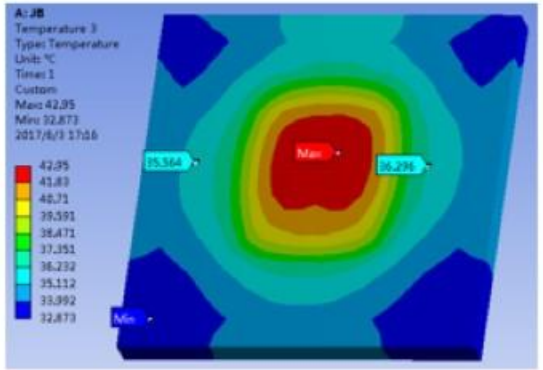
天线与电路板同时仿真



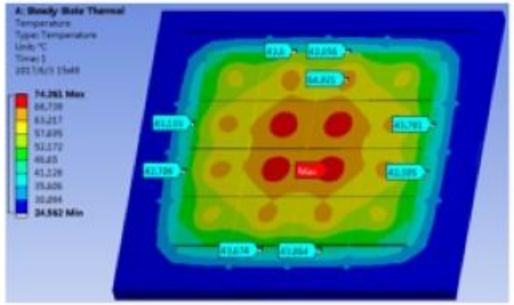
多物理分析



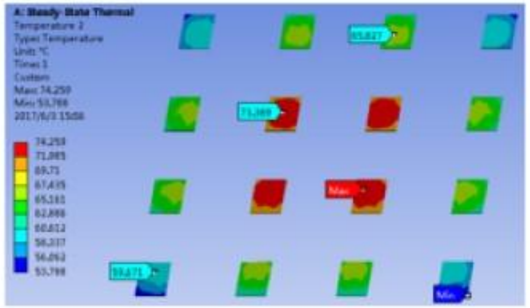




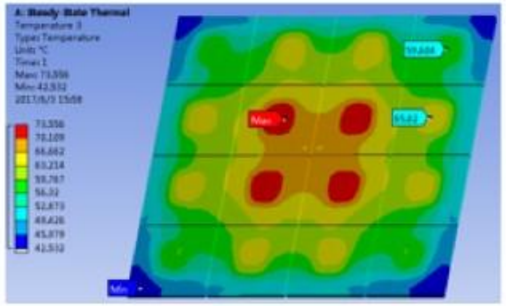
单芯片封装热分析



PCB+PKG



DIE



PKG

多芯片封装热分析

总结

- 大规模天线阵列、毫米波射频芯片与天线一体化设计将成为5G通信发展的趋势，其中毫米波封装天线具备高增益、高传输速率、低延时、低损耗的特性满足5G点到点通信标准。
- ANSYS 5G天线系统及多物理场仿真技术针对5G天线单元、天线阵列、复杂馈线、芯片封装与散热等端到端设计提供有效的解决方案。
- 5G仿真着重于射频前端、天线阵列、波束赋形、快速对准算法等精细化仿真，从软件高性能计算到多物理场可靠性综合分析。
- 5G通信将会给无线基站、CPE、移动终端、车联网等产品带来革命性的创新。
- 5G研发主要集中在无线回传、基站小站、终端移动、AR\VR、车联网等应用，预计在2020年后大规模商用。